QC
983
.A27

PL

MONTHLY WEATHER REVIEW

VOLUME 83 NUMBER 4

APRIL 1955

CONTENTS

	Page
Some Aspects of the Dynamics of Tornadoes.....Abdul Jabbar Abdullah	83
The Weather and Circulation of April 1955—Another Cold Month in the West.....Arthur F. Krueger	95
Weather Notes.....	94, 98
Correction.....	99
Charts I-XV	

U.S. DEPARTMENT OF COMMERCE • WEATHER BUREAU

PUBLICATIONS OF THE U. S. WEATHER BUREAU

As the national meteorological service for the United States, the Weather Bureau issues several periodicals, serials, and miscellaneous publications on weather, climate, and meteorological science as required to carry out its public service functions. The principal periodicals and serials are described on this page and on the inside of the back cover. A more complete listing of Weather Bureau publications is available upon request to Chief, U. S. Weather Bureau, Washington 25, D. C.

Orders for publications should be addressed to the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: Domestic, $3.00; Foreign, $4.00; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

WEEKLY WEATHER AND CROP BULLETIN

Issued on Wednesday of each week, the bulletin covers the weather of the week and its effects on crops and farm activities. Short reports from individual States are supplemented by maps of average temperature and total precipitation. In the winter months a chart of snow depth is included. Subscription: Annual, Domestic $3, Foreign $4; 10¢ per copy. For period December through March: Domestic $1.00, Foreign $1.50.

CLIMATOLOGICAL DATA—NATIONAL SUMMARY

This monthly publication contains climatological data such as pressure, temperature, winds, rainfall, snowfall, severe storms, floods, etc., for the United States as a whole. A short article describing the weather of the month over the United States, tables of the observational data, and a description of flood conditions are supplemented by 15 charts. An annual issue summarizes weather conditions in the United States for the year. More detailed local data are provided in the Climatological Data (by sections) for 45 sections representing each State or a group of States and Hawaii, Alaska, and the West Indies. Subscription price for either the National Summary or for a Section: $4.00 per year (including annual issue) domestic, $5.50, foreign; 30¢ per monthly issue; 50¢ for annual issue alone

(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 9, 1955.

DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 83
Number 4

APRIL 1955

Closed June 15, 1955
Issued July 15, 1955

SOME ASPECTS OF THE DYNAMICS OF TORNADOES

ABDUL JABBAR ABDULLAH

Department of Meteorology and Oceanography, College of Engineering, New York University*

[Manuscript received January 20, 1955; revised March 18, 1955]

ABSTRACT

In this paper an attempt is made to construct a dynamical model for a tornado that may explain some of its known features. The assumption is made that a tornado is dynamically equivalent to a combination of a pure sink and a pure vortex in the hydrodynamic sense. The compressibility of the air is taken into account, but the air is assumed to be dry. Friction is neglected and the motion induced by the disturbance is assumed to be horizontal.

It is found that, because of the compressibility of the air, the flow is separated into three main regions, an outer region in which the flow is subsonic, an innermost region which cannot belong to the outer flow, and a middle region that separates the two, in which the flow is supersonic. Formulas are derived by which the radii of these regions may be computed. The minimum possible pressure and the maximum possible speed are computed. The vertical shape of the funnel is also computed on the assumption that it is parallel to the surface of the critical flow.

CONTENTS

	Page
Abstract	83
1. Introduction	83
2. Qualitative description of the proposed theoretical model	84
3. The mature tornado	85
4. Mathematical analysis—the pure sink	86
5. Mathematical analysis—the mature tornado	88
6. The shape of the critical and limiting surfaces	91
7. The shape of the visible tornado column	91
8. Discussion and further remarks	92
Acknowledgment	93
References	93

1. INTRODUCTION

Various attempts have been made to construct a dynamic model for a tornado that may be compatible with observational facts. However, most of those attempts have run into some difficulties, either through internal incoherence arising in the theoretical model itself, or through contradiction with some observed facts. Indeed most of those attempts did not go far beyond the stage of mere speculations.

The obvious reason for the difficulty in constructing such a workable theoretical hypothesis is the lack of adequate observational data. Because of the extreme violence of these storms direct quantitative measurements have been next to an impossibility, especially in the core of the storm. This restriction on our knowledge has resulted in the accumulation of a variety of rather descriptive data which are far from the minimum requirements of mathematical treatment.

*The research reported in this paper has been sponsored by the Geophysics Research Directorate, Air Force Cambridge Research Center, under Contract AF 19(604)-1006.

Brooks [3] has stated that a major problem in explaining the formation of a tornado is to find the source of the potential energy and the manner in which it is converted into kinetic energy. The present writer wishes to modify this statement in the following manner. "A major problem in explaining the mechanics of tornadoes is to find the source of the kinetic energy and to account for its concentration over a rather small space." The present paper is an attempt to deal with this problem.

The leading thought in the present paper is similar to that expressed by Brunt [4 and 5] whose work was an extension of Rayleigh's [15] work. Brunt postulated that a strong convective vertical current on a rotating disc may be sufficient to initiate a vortex. His work implied that the "eviction" of air, caused by an ascending current, causes the pressure forces to do work on the air particles, and thus produce the kinetic energy required to initiate the disturbance. Because of the convergence of air toward the center of the disturbed area, and as a consequence of the conservation of angular momentum, kinetic energy is created and transported into the central region of the disc, and thus becomes concentrated there manifesting itself in the devastating winds.

Brunt, however, constructed his model on the assumption that the air may be considered as an incompressible fluid. This eliminated the possibility of the creation of kinetic energy by a transformation of internal energy. Moreover, the assumption of incompressibility introduces a singularity at the pole of the coordinate system, and provides no theoretical mechanism by which this singularity may be isolated from the main field of flow.

The present paper is an attempt to extend Brunt's hypothesis to a compressible atmosphere. Indeed the observed wind velocities around the core of a tornado, which are in the proximity of the sonic speed (Flora [8]), leave little doubt that the incompressibility approximation may introduce serious errors into the mathematical model.

2. QUALITATIVE DESCRIPTION OF THE PROPOSED THEORETICAL MODEL

Let it be assumed that, in the undisturbed state, the atmosphere is conditionally unstable, and that it consists of two main layers separated by a surface of inversion, this last condition being an auxiliary but not a necessary requirement. To simplify matters it is further assumed that the air is initially at rest or that it is in uniform horizontal motion. This assumption will be dropped after describing the first stage in the formation of the disturbance.

Because of some additional mechanism a centralized impulse is assumed to act at the inversion which separates the two layers. This impulse is assumed to be strong enough to break the inversion and to release the instability of the lower layer at the place of its action. It is not desirable to speculate, at this stage, on the nature of the mechanism that supplies this impulse, since the dynamic model to be described does not require any particular kind. However, some speculations on this point will be made at the end of this paper.

When the stabilizing inversion is broken at a small spot, the air of the lower layer suddenly becomes unstable and an ascending "current", which pierces the inversion at that spot, results. It is assumed that at a higher level conditions are favorable for the eviction of air, and the maintenance of the ascending jet. Here again no attempt is made to single out one factor that may be responsible for this process, but it may be mentioned that the existence of a swift horizontal jet at a higher level may be enough to do the job.

In order to visualize more clearly what happens when the lower fluid starts ascending at the unstable spot, it may be helpful to think of the process as though it were taking place in the following manner.

Let us assume, for simplicity, that the broken spot in the inversion surface is a perfect circle, and that the air in the cylindrical region below this surface is acted upon by the sudden impulse. The air in that cylinder may be thought of as a "piston" that is being acted upon by a force which pushes it upward parallel to the axis of the cylinder. As the piston moves, a rarefaction "wave" is initiated at the site and spreads radially outward with the local sonic speed, thus conveying the "news" of the strong disturbance to the surrounding air. This air responds by rushing radially inward toward the rarefied region. The creation of a rarefied region results in an unbalanced pressure gradient surrounding that region, which acts on the fluid particles in a radial direction. The particles starting from rest are accelerated in their motion toward the center. In the absence of non-conservative forces, the motion must necessarily be potential. To simplify matters it is sufficient for our present purpose to assume that radial symmetry exists, that the motion in the outer region is strictly horizontal, and that the outer flow at any horizontal plane is the same as that induced by a pure hydrodynamic sink placed at the geometric center of the inner circle.

It is well known that, under the law of a pure sink, an air particle that could reach the center of the sink should attain an infinite speed. But this does not happen. It will be shown, at another place in the present paper, that the inflowing particles can never come nearer to the center of the sink than a certain minimum distance at which their motion must come to a sudden halt. The inner circle surrounding the sink, which is prohibited to the outer flow, is known as the limiting circle, and its radius is called the minimum radius of the sink. The fluid is therefore divided into two separate regimes, an outside region which obeys the sink law and an inside region whose air does not belong to that of the outside region and whose flow does not obey the sink law.

It will be shown later that the velocity of the particles at the limiting circle is not infinite. Explicitly it is equal to the local sonic speed at that circle.

The physical reason for the establishment of the limiting circle is that the acceleration of the inrushing air particles increases as the particles approach the sink. At the limiting circle the acceleration becomes infinite, but the velocity remains finite. Hence in order to push a particle through the limiting circle the outer fluid must exert an infinite force, which is an impossibility.

Before going further in the present discussion, it may be fitting to say a word about the sources of the kinetic energy acquired by the inflowing fluid.

In a dry atmosphere subject to the horizontal flow being postulated, kinetic energy may be imparted to the particles from two main sources. First, the pressure forces that come into play because of the creation of the rarefied region, do work on the particles. This work is converted into kinetic energy. Second, because of the compressibility of the air, the air expands as it approaches the low pressure of the rarefied region and thus a part of its internal energy is converted into kinetic energy which is imparted to the air particles. In a saturated atmosphere, there is also a third source of energy available, namely the latent heat of condensation. As the limiting circle is approached the pressure is reduced, and hence the air particles expand and condensation may start. This source will be neglected in the present work since, although it may introduce some modifications in the magnitude of the quantities to be computed, it is not expected to change the qualitative results to any appreciable degree.

If the flow is strictly horizontal the air particles, drawn from the outer region, which reach the limiting circle, stop in the way of the inflowing particles that are rushing behind them. These latter particles have to slow down and be compressed before reaching the limiting circle. A circular shock wave is formed around the inner region. There is an annular ring of relatively high pressure caused by the compression of the air. The shock wave and its accompanying relatively high pressure move radially outward. The air particles behave as though they were reflected from a "wall" built at the limiting circle. This provides a blocking mechanism in the face of the process. There is now an outward flow superimposed on the original inflow, and the total effect is the same as that of superposition of a source on the original sink. The two would ultimately annul each other.

However, strict horizontal motion may be postulated only in the outer region. In the inner region ascending air exists.

The particles rushing from outside soon acquire a vertical component of motion as they approach the limiting circle. This hinders the formation of shock waves at lower levels and permits the successive particles to move farther toward the limiting circle, and then ascend behind the first particles. The rising air finally stops ascending when it reaches a certain equilibrium level. The "source" is therefore separated from the "sink" and placed at a higher level. The final picture in this process is that of a radial inflow at low levels and a radial outflow at higher levels, with a rarefied "cylindrical' column in the middle of the flow occupied by an ascending jet whose air does not belong to that of the outer region.

In order to keep this process going and to enable it to give birth to a tornado in its final stages, it is required that the vertical motion of the ascending "piston" must be sustained for a sufficiently long time. The energy required for maintaining this upward motion may be caused by the release of the latent instability. This becomes an important factor after the first impulse has stopped acting. This probably is the reason why tornadoes occur in conditionally unstable air with relatively low condensation level (see Fawbush and Miller [6 and 7]).

To sum up what has been mentioned so far about the envisaged process, it may be stated that if an initial state of complete stagnation and homogeneity is assumed, and if a pure sink line is initiated by some mechanism which persists for a sufficiently long time, the result would be the establishment of a rarefied column inside of which there is rising air, and outside of which there is radial flow. At lower levels the radial flow is an inflow, and at upper levels it is an outflow.

3. THE MATURE TORNADO

The discussion presented in the previous section has been based on the assumption that the initial state is that of complete rest or perfect uniformity. This condition is evidently rarely, if ever, realized in nature. There is normally some non-uniformity in the basic flow. Let us assume, therefore, that the basic flow is that of rotation superposed in translation, and consider the flow resulting from an initial sink travelling with the same velocity of translation.

When the air converges toward the rarified region in the manner described previously, its angular velocity increases as it approaches the center, in accordance with the law of conservation of angular momentum. The steady state approached by the disturbed flow is, therefore, that resulting from the superposition of a pure sink over a pure vortex. The air comprising the outer region is a field of radial inflow and rotation. The air particles in the outer region describe spiral paths as they approach the inner region. When they attain a vertical component of motion at the periphery of the inner region, they spiral upward. The inner column with the engulfing air will have the appearance of a "twister".

If there exists a swift narrow jet at a higher level, and if the sink line penetrates at its edge, it may be expected that the horizontal shear across the sink superposes, on the converging air, a stronger rotation. In other words, the "vortex" strength may be expected to increase with height under these conditions.

Because the rotation results from the concentration of a pre-existing field, it may be concluded that the sense of rotation must be cyclonic in a cyclonic flow, and anticyclonic in an anticyclonic flow. This is probably the

reason why most of the observed tornadoes have a cyclonic sense of rotation, since tornadoes are more frequent in a cyclonic flow.

When the disturbance attains rotation in the described way, the tornado is in its mature stage. On the rough terrain where friction acts strongly, the ground layer of the tornado column is in the boundary layer of the flow. It is well known that in the boundary later the steady flow is nearly parallel to the pressure gradient (see Goldstein [9]). The flow in this layer is therefore expected to be nearly radially inward. This is probably the reason why some tornadoes are reported to have no rotation. It may be remembeed that the wind direction in a tornado is mostly judged by its effects on the movements of obstructions which exist on the ground.

In anticipation of the results of the mathematical analysis to be presented later, it may be mentioned that when a vortex superposes itself on a sink it acts as a stabilizing factor on it. The minimum radius of the limiting circle is much larger now than its magnitude in the pure sink case. The spiraling air particles may attain much higher velocities. In fact, there will be established an annular ring of supersonic flow, around the limiting circle, in which the velocity of the air particles surpasses the local sonic velocities. The whole field of flow is now divided into three different regimes: an outermost field in which the flow is subsonic, an innermost circular field whose flow does not belong to the outer flow, and an annular ring separating the two regions in which the flow is supersonic. The radius of the innermost region, i. e., of the limiting circle, is the minimum radius. The outer radius of the supercritical region will be called the "critical" radius. The circle surrounding the supercritical region will be called the "critical" circle. The speed of the air particles at the critical circle is equal to the local speed of sound.

If conditions are invariant with height, one may then speak of a limiting cylinder and a critical cylinder in an obvious extension of the two-dimensional picture. If conditions vary with height, as they in general do, then one speaks of a limiting surface and a critical surface. An example of an idealized simple model will be given later. The shapes of the surfaces of that model will be computed.

It may be mentioned here that the supersonic regime cannot live, in nature, for an appreciable period of time. A supersonic flow is highly sensitive to obstructions. Shock waves soon develop, in that regime, which feed on its kinetic energy and eventually destroy it. These shock waves provide the mechanism to disturb the flow in the supersonic regime and allow the air to "leak" into the inner region, a mechanism which must be very effective in the eventual decay of the tornado.

4. MATHEMATICAL ANALYSIS—THE PURE SINK

Let a cylindrical polar system of coordinates be chosen in such a way that the axis points vertically upward and coincides with the center of the initial hydrodynamic sink. For the sake of simplicity friction will be neglected. Moreover, because of the rapidity of process, it is assumed that adiabatic conditions exist. The air is assumed to be dry and no condensation takes place during its horizontal motion.

The equation of motion may be written in the following form.

$$\frac{d\mathbf{q}}{dt}+2\boldsymbol{\omega}\times\mathbf{q}=-\frac{1}{\rho}\nabla p-\mathbf{k}g \tag{1}$$

where $\mathbf{q}$ is the velocity, $\boldsymbol{\omega}$ is the angular velocity of the earth's rotation, ρ is the density, p the pressure, g the acceleration of gravity, and $\mathbf{k}$ is the unit vector in the vertical direction.

Upon multiplying (1) scalarly by $\mathbf{q}$ this equation yields the following:

$$\frac{d}{dt}\left(\frac{1}{2}q^2+\frac{p}{\rho}\right)-p\frac{d}{dt}\left(\frac{1}{\rho}\right)=\frac{1}{\rho}\frac{\partial p}{\partial t}-gw \tag{2}$$

where w is the vertical component of the velocity.

Under dry adiabatic conditions the first law of thermodynamics is the following:

$$0=c_v\frac{dT}{dt}+p\frac{d}{dt}\left(\frac{1}{\rho}\right) \tag{3}$$

where c_v is the specific heat for constant volume, and T is the absolute temperature.

The equation of state for dry air is the following:

$$p=(c_p-c_v)\rho T \tag{4}$$

where c_p is the specific heat under constant pressure.

Upon combining (2), (3), and (4) and assuming steady case, integrating along a streamline, Bernoulli's equation is derived in the following form (see Haurwitz [10]):

$$\frac{1}{2}q^2+\frac{\gamma}{\gamma-1}\frac{p}{\rho}+g\Delta h=\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0}+\frac{1}{2}q_0^2 \tag{5'}$$

where Δh is the vertical distance that an air particle has moved between its initial and final positions; p_0, ρ_0, q_0 refer to the values at infinity and $\gamma=c_p/c_v$.

Let us now assume that we are interested only in the motion of the outside field where it is mainly horizontal, and let the fluid at infinity be at rest with respect to the system of coordinates. Equation (5′) then simplifies to the following form:

$$\frac{1}{2}q^2+\frac{\gamma}{\gamma-1}\frac{p}{\rho}=\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0} \tag{5}$$

The adiabatic law of expansion is the following:

$$p=\epsilon\rho^\gamma \tag{6}$$

where ϵ is a constant.

The local speed of sound is given by the following relation:

$$c^2=\frac{dp}{d\rho}. \tag{7}$$

Upon combining (6), (7), and (5), Bernoulli's equation takes the following form:

$$\frac{1}{2}q^2+\frac{c^2}{\gamma-1}=\frac{c_0^2}{\gamma-1}=\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0} \tag{8}$$

where c_0 is the sonic speed at infinity.

Define the Mach number μ by the following relation:

$$\mu\equiv\frac{q}{c} \tag{9}$$

Upon introducing this number in (8), Bernoulli's equation takes the following form (see Milne-Thomson [13]):

$$1+\frac{1}{2}(\gamma-1)\mu^2=\frac{c_0^2}{c^2}=\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}} \tag{10}$$

Now assume that a pure sink is placed at the pole of the coordinates, and consider the flow at any horizontal layer of unit thickness. Let the input of mass into the "two-dimensional" sink be $2\pi m$ per unit time, and let v be the radial speed at a distance r from the sink. The equation of continuity gives the following relation:

$$rv=\frac{m}{\rho} \tag{11}$$

Let it first be assumed that the pure sink is at rest with respect to the flow, and that the field of motion is purely radial, and no tangential velocity exists. In other words, $v=q$ in this case.

From (11) and (10) the following relation is obtained (see Milne-Thomson [13]):

$$r=\frac{m}{c_0\rho_0\mu}\left(1+\frac{\gamma-1}{2}\mu^2\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{12}$$

This relation gives the radial distance of a particle in the field as a function of the dimensionless number μ. If a ring of particles surrounding the sink is considered, then r represents the radius of that ring.

By differentiation of (12) with respect to μ, it is easily verified that r has a minimum value at the point $\mu=1$ (see Milne-Thomson [13]). The minimum radius that a ring may attain, while it is being contracted during its convergence, is therefore given by the following equation:

$$r_{sm}=\frac{m}{c_0\rho_0}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{13}$$

The sink, therefore, can induce inward motion only outside a circle whose radius is r_{sm} as given by equation (13). This circle is the "limiting" circle. The motion inside it cannot obey the same law as that outside it. Since at the limiting circle $\mu=1$, relation (9) shows that the speed of the air particles at this circle is equal to the local speed of sound. In the outer flow, since the air at infinity is at rest, the velocity is less than that of sound. Hence subsonic flow exists everywhere except right at the limiting circle where sonic speed is approached.

In the steady case the acceleration of a particle in the outer flow is given by the following relation:

$$\alpha=v\frac{dv}{dr}. \tag{14}$$

This may be written as follows:

$$\alpha=v\frac{dv/d\mu}{dr/d\mu} \tag{14'}$$

At the limiting circle we have, by definition

$$\frac{dr}{d\mu}=0.$$

Hence, at the limiting circle $\alpha=\infty$ (see Howarth [11]). This shows that in order that a particle may reach the limiting circle, an infinite force has to act on it, which is an impossibility. This result was anticipated in the discussion given in the previous section.

For air $\gamma=7/5$. Upon using the value in equation (13), the latter becomes as follows:

$$r_{sm}=\frac{m}{c_0\rho_0}\left(\frac{6}{5}\right)^3=\frac{1.728m}{c_0\rho_0} \tag{15}$$

Because

$$c=\sqrt{\gamma R^*T} \tag{16}$$

where R^* is the gas constant, it is seen from equation (15) that the radius of the limiting circle is directly proportional to the sink strength measured in volume (m/ρ_0) and inversely proportional to the square root of the temperature of the undisturbed air at infinity.

For a first orientation on the order of magnitude of the minimum radius in the case of a pure sink let us consider the following values. Let $c_0=330$ m./sec., $\rho_0=10^{-3}$ gm. cm.$^{-3}$, and let the sink have such a strength that it induces a radial velocity of 1 cm./sec. at a point 40 km. away from its center.

From (11), it follows that $m=4\times10^3$ c.g.s.u. This is a rather weak sink which may be caused by rising air over a circular area of radius 200 meters, with a vertical velocity of 10 m./sec., if the air for the rising column is drawn over a height of 1 km.

With these values, equation (15) gives the radius of the limiting circle to be 2.1 meters.

The pressure at the limiting circle may be computed from equation (10) after giving μ the value 1. That equation becomes as follows, with $\gamma=7/5$,

$$\frac{p_0}{p}=\left(\frac{6}{5}\right)^{7/2}=1.893. \tag{17}$$

If the pressure at infinity is assumed to be 1000 mb., the pressure at the limiting circle is found to be 530 mb. This value may be taken to represent the pressure at the center of the disturbance since it cannot be far from it. It may be seen that the computed pressure is too low compared with some observations on tornadoes which estimate that pressure to be about 800 mb. (Brooks [3]). This difference may be due to two reasons. First no actual observation is known to have been taken right at the center of the tornado, since most observations have been taken in the neighborhood of the column. Second, in the computed value, it has been assumed that the particles actually reach the limiting circle; but from the physical reasoning given before, it has been shown that this circle may be approached but never reached. Hence the computed value may be considered as the minimum value that may be approached under the conditions described above.

The velocity of the inrushing air at the limiting circle may be computed from equation (10), since at that circle $v_{max}=c$. That equation yields the following relation:

$$v_{max}^2=\frac{5}{6}c_0^2 \tag{10a}$$

Upon substituting the assumed value for c_0, it is found that the velocity $v_{max}=301$ m./sec. Here again the computed value may be somewhat higher than the value estimated on the basis of observation, and it must be considered as a maximum limit for the wind velocity.

5. MATHEMATICAL ANALYSIS—THE MATURE TORNADO

In the mature tornado it is postulated that the converging air of the outer region acquires rotation which is superposed on its inward motion. If the motion remains strictly horizontal, and if there is some pre-existing rotation in the undisturbed field, Brunt [5] has shown that a true vortex motion results. The total motion in the outside field is therefore that of a combined sink and vortex. Lewis and Perkins [12] have shown that this theory is in good agreement with some observations.

Let the vortex strength at any horizontal layer be κ, and the tangential component of velocity, induced by the vortex at a point which is at a distance r from the center, be u. The following relation is valid:

$$u=\frac{\kappa}{r} \tag{18}$$

The combined flow of the vortex and the sink at that layer obeys the following law:

$$q=\sqrt{\frac{m^2}{\rho^2}+\kappa^2}\,\frac{1}{r} \tag{19'}$$

This equation may be written in the following form:

$$r^2=\frac{1}{q^2}\left(\frac{m^2}{\rho^2}+\kappa^2\right) \tag{19}$$

Upon combining this and equation (10), the following relation results:

$$r^2=\frac{m^2}{c_0^2\rho_0^2\mu^2}\left(1+\frac{\gamma-1}{2}\mu^2\right)^{\frac{\gamma+1}{\gamma-1}}+\frac{\kappa^2}{c_0^2}\left(\frac{1}{\mu^2}+\frac{\gamma-1}{2}\right) \tag{20}$$

In order to determine the minimum radius of the combined flow, equation (20) may be differentiated with respect to μ, and the result equalized to zero. The stationary values of μ are then found to satisfy the following equation:

$$-\left(1+\frac{\gamma-1}{2}\mu_s^2\right)^{\frac{\gamma+1}{\gamma-1}}+\frac{\mu_s^2}{2}(\gamma+1)\left(1+\frac{\gamma-1}{2}\mu_s^2\right)^{\frac{2}{\gamma-1}}=\frac{\kappa^2\rho_0^2}{m^2} \tag{21}$$

where μ_s is the stationary value of μ.

In the case of dry air $\gamma=7/5$. Upon using this value equation (21) takes the following form:

$$-\left(1+\frac{\mu_s^2}{5}\right)^6+6\,\frac{\mu_s^2}{5}\left(1+\frac{\mu_s^2}{5}\right)^5=\lambda^2 \tag{22}$$

where

$$\lambda=\left|\frac{\kappa\rho_0}{m}\right| \tag{23}$$

λ gives the ratio between the vortex strength and the sink strength expressed in units of volume.

Upon putting

$$X=\frac{\mu_s^2}{5} \tag{24}$$

equation (22) takes the following form.

$$5X^6+24X^5+45X^4+40X^3+15X^2-1=\lambda^2 \tag{25}$$

This equation possesses one real root only, hence there is only one minimum point in the $r-\mu$ curve. The first column of table 1 gives the values of this root corresponding to different values of λ.

TABLE 1.—*The first column gives the stationary values of the Mach number μ_s corresponding to the assumed values of the strength parameter λ_s: which is given in column 2. The third column gives the values of the non-dimensional minimum radius R_m; the fourth gives the corresponding non-dimensional critical radius R_c, and the last column gives the non-dimensional width of the supersonic region ΔR.*

μ_s	λ_s	R_m	R_c	ΔR
1	lm	lm	-------	---------
1	0	1.728	1.728	0
1.225	1.36	2.2	2.29	.09
1.323	1.79	2.43	2.65	.22
1.414	2.32	2.74	3.09	.35
1.5	2.83	3.06	3.57	.51
1.581	3.37	3.37	4.09	.72
2	7.53	5.83	8.45	2.62
2.236	11.31	8.0	11.56	3.56
3.16	46	26.66	50.6	24.0
3.873	119	64	131	67
4.472	223	114.7	245	130
5	428	214.1	471	257
∞	∞	∞	-------	---------

Table 1 shows that μ_s has the value unity when λ_s is zero. This corresponds to the case of a pure sink which was discussed in the previous section. It is also seen from this table that $\mu_s > 1$ when $\lambda > 0$. This means that in the combined case the flow may become supersonic at the limiting circle. The maximum velocity, namely the velocity of the flow right at the limiting circle tends to increase as the ratio λ increases. When λ becomes infinity, i. e., when the sink strength vanishes and only the vortex is effective, the local Mach number tends to infinity. This may happen if the local sonic speed tends to zero. This case calls for a complete vacuum at the inner core of the vortex, a condition which is rather far from realization in nature, and may be considered as a pure mathematical concept.

It may easily be verified, in a way similar to that outlined in the previous section, that the acceleration approaches infinity as the limiting circle is approached. Hence it may be concluded that the particles belonging to the outer flow never reach that circle but they may approach it asymptotically. Upon the introduction of a vertical component of velocity in the neighborhood of the limiting circle, it follows again that the air particles in that region spiral upward in the manner described before.

Returning to equation (20), and substituting μ_s for μ, the minimum radius that may be attained by a contracting ring may be found. This radius is the same as that of the limiting circle at the horizontal layer under consideration. Before doing so, it may be advantageous to introduce a dimensionless minimum radius R_m defined by the following identity:

$$R_m \equiv \frac{c_0 \rho_0}{m} r_{min}. \tag{26}$$

Equation (20) gives for R_m, after using the proper value of γ, the following:

$$R_m = \left\{ \left(\frac{1}{\mu_s^2} + \frac{1}{5} \right) \left[\left(1 + \frac{\mu_s^2}{5} \right)^5 + \lambda_s^2 \right] \right\}^{1/2} \tag{27}$$

The quantity γ_s was used to indicate that the value of γ appropriate for the stationary value μ_s must be used.

The third column in table 1 gives the values of R_m computed from equation (27).

The region inside of which the flow is supersonic is an annular ring surrounding the limiting circle. Its outer radius is the critical radius and is given the symbol r_c. It may be emphasized here that the accelation at this circle is not infinity in this case of the combined flow. Hence the air may cross this circle since it offers no physical barrier. This barrier is now removed inwards to the limiting circle.

Upon putting $\mu = 1$ in equation (20), and using the appropriate value for γ, the following value is obtained for r_c:

$$r_c = \frac{m}{c_0 \rho_0} \sqrt{\frac{6}{5}} \sqrt{\left(\frac{6}{5} \right)^5 + \lambda^2} \tag{28}$$

This may be expressed in terms of a dimensionless critical radius R_c defined by the indentity:

$$R_c \equiv \frac{c_p \rho_0 r_c}{m}. \tag{29}$$

It then takes the following form:

$$R_c = \sqrt{\frac{6}{5}} \sqrt{\left(\frac{6}{5} \right)^5 + \lambda^2}. \tag{30}$$

The values of R_c corresponding to the appropriate values of λ are given in the fourth column of table 1. The fifth column of that table gives $\Delta R = R_c - R_m$. This is a measure of the width of the supersonic region.

In the hypothetical case of a pure vortex, when there is no sink, R (where $R \equiv c_0 \rho_0 r / m$) cannot be taken as a parameter since it attains an infinite value. In this case, however, equation (20) reduces to the following form

$$r = \frac{\kappa}{c_0} \left(\frac{1}{\mu^2} + \frac{\gamma - 1}{2} \right)^{1/2} \tag{31}$$

The minimum radius may be obtained from this equation by putting $\mu = \infty$. Upon using the appropriate value for γ, the minimum radius for the vortex case is found to be the following:

$$r_{vm} = \frac{\kappa}{c_0 \sqrt{5}} \tag{32}$$

The critical radius for the pure vortex may also be found from (31) by putting $\mu = 1$. Thus it is found to have the following value:

$$r_{vc} = \frac{\kappa \sqrt{6}}{c_0 \sqrt{5}} \tag{33}$$

The width of the supersonic ring is, in this case,

$$\Delta r = r_{vc} - r_{vm} = \frac{1.45}{\sqrt{5}} \frac{\kappa}{c_0}$$

or

$$\frac{\Delta r}{r_{vm}} = 1.45 \tag{34}$$

This value also gives the maximum fractional width that may be assumed by the supersonic ring.

It may be stated again that the case of a pure vortex, without a sink, is a physical impossibility because it requires a complete vacuum at the inner core, as has already been shown. However, the combined vortex-sink is always possible. The only alternative, according to the present analysis, is a pure sink which calls for initial conditions that are very hard to realize. Table 2 gives the values, in meters, of the minimum radius and the critical radius for a combined vortex-sink flow. The following assumptions are made. The radial velocity is assumed to be 1 cm./sec. at a distance of 40 km. from the center. The sonic speed at infinity is assumed to be

TABLE 2.—*The values, in meters, of the minimum radius r_m, and of the critical radius r_c, and the fractional width of the supersonic flow $\Delta r/r_m$, for a combined vortex-sink flow which has the indicated stationary values of the Mach number μ_s and the corresponding stationary values of the strength parameter λ_s*

μ_s	λ_s	r_m	r_c	Δr	$\Delta r/r_m$
1	0	2.09	2.09	0	0
1.225	1.36	2.67	2.78	.11	.04
1.323	1.79	2.94	3.22	.28	.095
1.414	2.32	3.33	3.75	.42	.127
1.5	2.83	3.71	4.32	.61	.164
1.581	3.37	4.09	4.96	.87	.215
2	7.53	7.1	10.3	3.2	.45
2.236	11.31	9.70	14.0	4.30	.443
3.16	46	32.2	60.3	28.1	.872
3.871	119	77.5	158	80.5	1.03
4.72	223	139	296	157	1.13
5	428	259	570	311	1.20
∞	------	------	------	------	1.45

$m=4\times10^{5}$; $c_0=3.3\times10^{4}$; $\rho_0=10^{-3}$; $r=1.21\times10^{6}R$

$c_0=3.3\times10^4$ cm./sec. and the undisturbed density $\rho_0=10^{-3}$ gm./cm^3.

The last two columns of table 2 give the width of the supersonic zone in meters, and its fractional width, respectively. It may be seen from the values given there that the width of this zone increases, in general, with increasing values of λ. The fractional width approaches the value 1.45 as λ approaches ∞, which is the pure vortex case.

In connection with the computed values of the radius of the tornado as outlined above, the following remarks may be made.

First, the observed and reported radius of a tornado is expected to be much greater than the computed values of the critical radius, the reason being that observers estimate the size of a tornado looking at it from outside and at a safe distance away from it. Their estimates are based on dust and other debris that float in the circulation. Obscurities of this nature are usually carried in the region of strong winds which surrounds the critical radius and may have an appreciable extent in the horizontal. The winds reach destructive force long before sonic speed is approached.

As a rough example, assume that the outer fringes of the destructive area have a wind force of a whole gale. The Beaufort scale describes such a wind to be capable of uprooting trees and of causing considerable structural damage. The speed of such a wind is about 100 km. per hour. This is about one tenth of the sonic speed at normal temperature. Since the wind velocity is nearly equal to the undisturbed sonic velocity at the critical circle, it follows that the outer radius of the area of distruction is about ten times greater than the critical radius. Thus in the case of the smallest computed twister given in table 2 where $r_c=2.78$ meters, the "radius of destruction" is about 28 meters.

Second, as has been stated before, the supersonic region is very sensitive to minor obstructions and soon develops shock waves which act to destroy that region. Hence the maximum wind velocity that may occur at the ground level is not expected to exceed that of sound. If supersonic flow is established, it is not expected to last for any appreciable period of time at the ground level. Supersonic speeds may, however, last for a longer period in the free air at higher levels. At those levels sonic speed is normally smaller than its value at the ground because the temperature normally decreases with height.

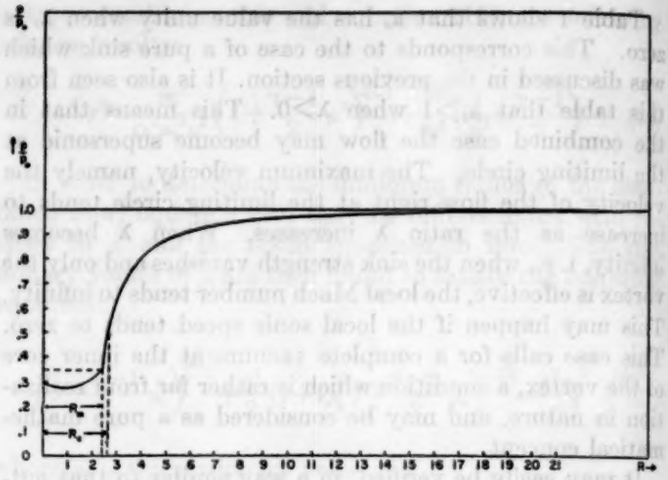


FIGURE 1.—Schematic plot of the variation of pressure with distance from the center of a mature tornado. The abscissa is the dimensionless radius R and the ordinate is p/p_0, where p_0 is the pressure at the undisturbed air. R_e is the dimensionless critical radius, and R_m is the dimensionless minimum radius. The curve was arbitrarily continued inside the limiting circle.

The pressure at the critical circle may be computed from equation (17), and the wind velocity at that circle may be computed from (10a). They will be found to have the same values as computed in the previous sections.

The pressure at the minimum circle, and the sonic speed at that circle may be computed from equation (10), after giving μ the value μ_s. That equation, for air, takes the following form:

$$1+\frac{\mu_s^2}{5}=\frac{c_0^2}{c^2}=\left(\frac{p_0}{p}\right)^{2/7} \tag{10b}$$

The wind velocity at the limiting circle may be found from (9).

Figure 1 is a plot of p/p_0 against R in the case of $\lambda=1.79$. It can be seen from this figure that the pressure remains almost unaffected until R is 10; then it starts decreasing more and more rapidly as R_c is approached. Between R_c and R_m the slope of p/p_0 becomes almost vertical. The behavior of the pressure inside the limiting circle cannot be predicted from the present theory, and therefore it is shown in the figure as an arbitrary line. The region between R_c and R_m, which is the supersonic region, may be greatly modified in the natural phenomenon, since this marks the unstable region where shock waves are expected to develop. An actual trace may even show a secondary maximum at this region because of the compression of air in the shock region.

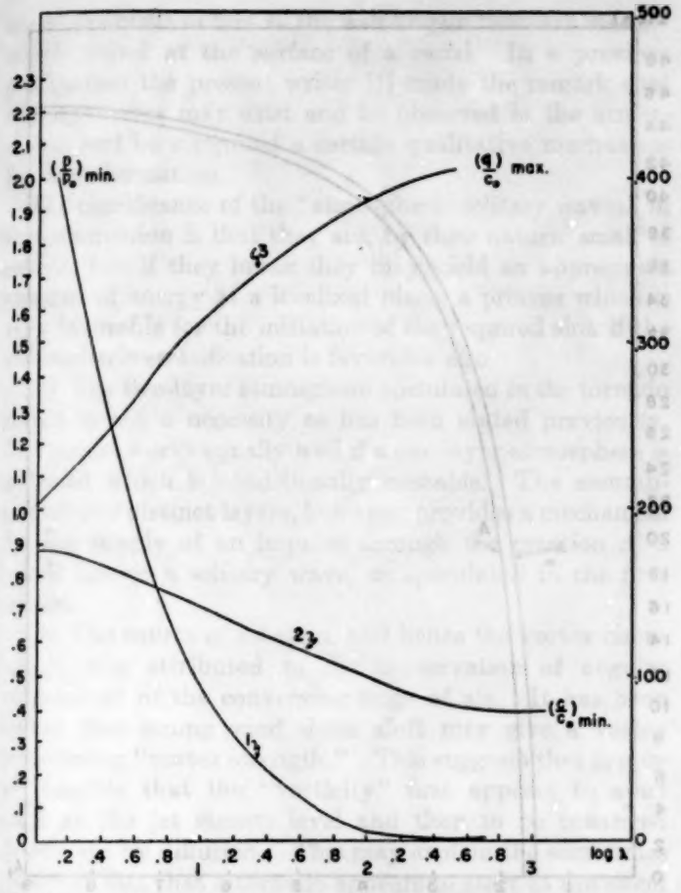


FIGURE 2.—Curve 1 is a plot of $(p/p_0)_{min}$ against log λ. The values of $(p/p_0)_{min}$ must be read on the right hand scale. Curves 2 and 3 are plots of $(q/c_0)_{max}$ and $(c/c_0)_{min}$ against log λ. The values of these variables are to be read on the left hand scale. The values of the three indicated variables are given as functions of the single parameter λ.

Figure 2 is a plot of $(p/p_0)_{min}$, $(q/c_0)_{max}$, and $(c/c_0)_{min}$ against log λ. These are the values at the limiting circle.

6. THE SHAPE OF THE CRITICAL AND LIMITING SURFACES

It has been stated previously that in three dimensions one must speak of a limiting surface and a critical surface. The horizontal cross-sections of these surfaces at any level are the same as their corresponding circles, on the assumption of complete radial symmetry.

The radius of the limiting circle, r_{sm}, may be computed, at any level, from equations (27) and (26). It can be seen from these equations that r_{sm} is a function of the sink strength m, the undisturbed sonic speed c_0, the undisturbed density ρ_0, and the vortex strength κ. In general all of these quantities vary with height, and the exact shape of the limiting surface can be ascertained only after knowing, explicitly, the fundamental relationships between these quantities and height. These functional relationships are expected to change from one individual storm to another. Therefore the surface shape is expected to change accordingly.

Similarly, the critical radius may be computed from equations (29) and (30). It is seen from those equations that the same thing is true in this case also.

In order to obtain a first rough concept of the general shape of these surfaces, the following idealized case will be discussed.

Let m/ρ_0 and κ be independent of height. It then follows from equations (27) and (30) that R_m and R_c are invariants with respect to height. From (26) and (29) it follows that

$$R_i=\frac{c_0\rho_0}{m}r_i;\ (i=m,c)$$

But

$$c_0=\sqrt{\gamma R^* T_0} \tag{16'}$$

Therefore

$$r_i=\frac{m}{\rho_0}\frac{1}{\sqrt{\gamma R^* T_0}}R_i \tag{35}$$

Since m/ρ_0 has been assumed to be a constant, it is seen from this equation that r_i is inversely proportional to the square root of the undisturbed temperature.

Let the temperature be given by the following linear relation:

$$T_0=T_s-\beta z \tag{36}$$

where T_s is the temperature at the ground, and β is a constant lapse rate.

Equation (35) may then be written in the following form:

$$r_i=\frac{m}{\rho_0}\frac{R_i}{\sqrt{\gamma R^*}}\frac{1}{\sqrt{T_s-\beta z}} \tag{37}$$

or

$$A_i\equiv\sqrt{\gamma R^*}\frac{\rho_0}{m}r_i=R_i(T_s-\beta z)^{-1/2} \tag{38}$$

Figure 3 is a plot of A_i against z. In this figure the following values were assumed. $T_s=280°$K, $\beta=6°$ per km., $R_m=2.43$, and $R_c=2.65$. These last values are the same as those used in figure 2, and they correspond to $\lambda=1.79$.

It may be seen from this figure that both surfaces are hyperbolic, with an asymptote at $z=46.4$ km.

Needless to say, the assumptions of constancy that have been made here are crude, and the figure is meant only to give an idea of the general, but not the exact, shape of those surfaces.

7. THE SHAPE OF THE VISIBLE TORNADO COLUMN

The process responsible for the formation of a tornado, envisaged in the present paper, requires an initial line sink established in the atmosphere, probably through the rise of an accelerated vertical jet. It may therefore be surmised that the general shape of the tornado column is that of its "nucleus" sink.

The jet, in general, does not ascend along a vertical straight path, first because it is affected by the horizontal winds at the various levels which it penetrates, and second

because, in its ascent, it follows the path of least resistance. This latter restriction is caused by the variation in the degree of stability of the various parts of the air along its path. It therefore may be surmised that a tornado column may assume various shapes, such as the snake shape or the rope shape, so frequently reported. The "branched" tornado column may be explained on the assumption of two rising jets merging together, or one jet splitting into two depending upon the sense of branching.

The horizontal cross section of the tornado column is rather hard to compute analytically. The column becomes visible only because of the opaque obscurities that are suspended in the circulation. At the ground level dust particles and floating solid bodies may be carried, and the shape of the column in those levels may be a function of the wind force and the size of the available particles.

In the free atmosphere the column becomes visible because of its associated cloud. It has been shown in the mathematical analysis that the pressure is greatly reduced as the inner core of the column is approached. An air particle moving toward the inner core expands adiabatically, and condensation may take place when its condensation pressure level is reached. This may happen some distance before either the limiting surface or the critical surface is reached. In general it is possible to compute the condensation point, and hence the general shape of the tornado cloud, at the various levels once an ascent in the undisturbed air is known. However, this is not attempted in the present paper, since the assumption of dry air was taken as a starting point. Instead it is assumed that the "cloud surface" may be taken as being parallel to the critical surface. Hence the general shape in figure 3 may also be taken to represent the shape of a vertical tornado column.

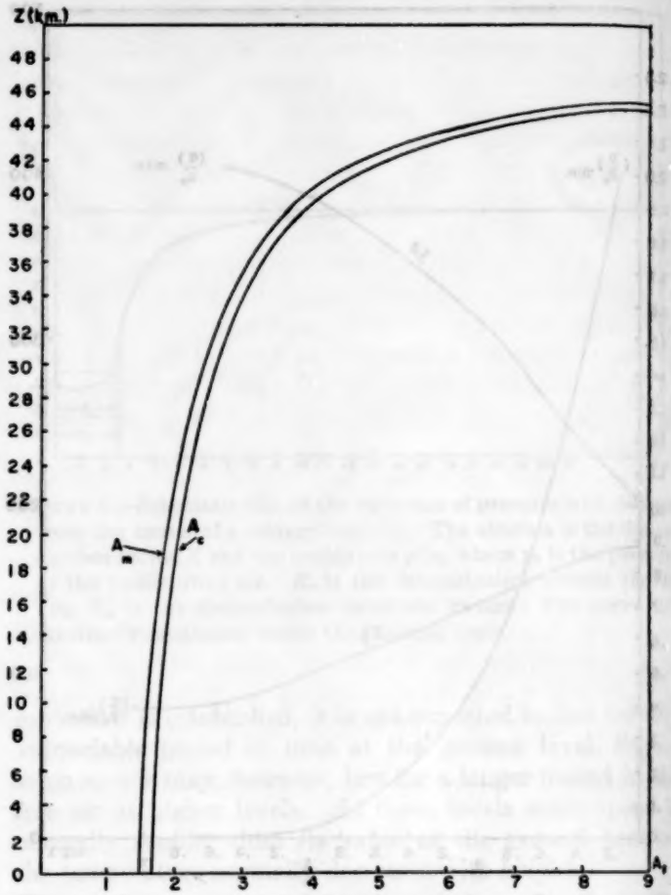


FIGURE 3.—Schematic representations of the general shapes of the limiting surface and the critical surface in a vertical tornado column. The abscissa A_i is a dimensionless radius and the ordinate z is the height in kilometers. A_m refers to the limiting surface, and A_c to the critical surface.

8. DISCUSSION AND FURTHER REMARKS

On the basis of the foregoing analysis it may be surmised that an idealized dynamical model, based on the combination of a simple sink and a simple vortex, may serve to explain a number of the observed facts about tornadoes. There are, however, many factors that come into play and must be effective in the actual phenomenon, which have been neglected in this model either for the sake of mathematical simplicity or for lack of adequate quantitative data. The present model, therefore, admits of a number of improvements along which further work may be carried if seen feasible. The following qualitative remarks which are basically speculative in nature are added with the intention of criticizing the theoretical model, and of suggesting some physically possible improvements.

(1) The model assumes the existence of a line sink in the atmosphere that persists for an appreciable period of time which must be long enough to permit the disturbed flow to approach a final state of equilibrium. It has been mentioned that the sink may conceivably be, and most probably is initiated by a rising current which in turn is caused by the breakdown of stability at a small spot. The idea that the causing impulse must be limited in size to a small region seems to be most adequate for the initiation of a rather strong and well organized "jet" which does not admit internal convective activity that may lead to confused motion.

Such a strong but limited impulse may conceivably be caused by the "falling" down of an overhanging "hump" of cold air, in the way that is thought to happen when "breaking" takes place in the process which leads to the formation of a pressure jump line. This mechanism was first suggested to be responsible for tornado formation by Tepper [17], who in addition suggested that the intersection of two jumps may be more favorable for this process. Newstein [14] has found that tornadoes occur in the area affected by a pressure jump, which result gives further support to this idea.

Another possible mechanism which may supply a localized impulse is the migrating micro-anticyclones called "bubbles" by Fawbush and Miller [7]. It will be shown in a forthcoming publication that these "bubbles"

are of the same nature as the well known "solitary waves" which travel at the surface of a canal. In a previous publication the present writer [1] made the remark that solitary waves may exist and be observed in the atmosphere, and he suggested a certain qualitative mechanism for their formation.

The significance of the "atmospheric solitary waves" in this connection is that they are, by their nature, small in extent; but if they break they may yield an appreciable amount of energy at a localized place, a process which is very favorable for the initiation of the required sink if the atmospheric stratification is favorable also.

(2) The two-layer atmosphere postulated in the tornado model is not a necessity as has been stated previously. The model works equally well if a one-layer atmosphere is assumed which is conditionally unstable. The assumption of two distinct layers, however, provides a mechanism for the supply of an impulse through the creation of a squall line or a solitary wave, as speculated in the first remark.

(3) The source of rotation, and hence the vortex circulation, was attributed to the conservation of angular momentum of the converging rings of air. It has been stated that strong wind shear aloft may give a vortex with strong "vortex strength." This suggests that it may be possible that the "vorticity" first appears to start aloft at the jet stream level and then to be conveyed downward by diffusion. This may explain the sometimes observed fact that a tornado appears to start at the cloud level and then build itself downward.

(4) In the computed examples, the sink strength expressed in volume units, namely m/ρ_0, has been assumed to be a constant. It may appear at the first instant that this is a far fetched assumption, and it may be thought that most of the air involved in the rising current is drawn from the lower layers. It is known, however, (see for instance Stommel [16]) that a cumulus cloud entrains a considerable volume of air at various levels. Rough analysis made on the data given in Stommel's paper convinced the writer that the sink strength is well maintained to the top of the cloud. There are, naturally, some variations in the value of the entrained air, but it may safely be said that the sink extends to higher levels with its strength being kept up by the entrained air. In tornado formation entrainment must be expected to be much greater than that in the case of ordinary cumulus clouds, because of the greater vertical accelerations involved.

(5) It has been stated by various observers that destruction in a tornado is caused by the low pressure at the core, as well as by the strong winds of the circulation. It may be seen from figure 2 that the pressure falls considerably only when the critical radius is approached. The pressure gradient at that point must be very great. However, strong and destructive winds extend over a wider area, and may safely be assumed to engulf the area of destructive pressure. In making an estimate of the area of destruction, only wind strength has been taken into account, it being understood that this area includes the area of destructive pressure.

(6) A word may be added about the similarity of the dynamical model proposed here for a tornado and that proposed by the author for a hurricane in a previous publication [2]. It seems that the two models are quite similar. The main differences are first, that the compressibility of the air is neglected in the hurricane model because the velocities are always much smaller than that of sound; and second, in the hurricane model a pure vortex motion is possible whereas this is not physically possible for a tornado. The reason that the vortex is possible in a hurricane is the assumption of a two-layer atmosphere. The "vacuum" produced in the lower layer by the vortex motion is filled by air of the upper layer.

(7) The assumption that a tornado circulation is dynamically equivalent to a combination of a sink and a vortex provides the embryo for the decay of the tornado. As explained before, the field of the combination results in the creation of a supersonic region which surrounds the limiting circle. This region develops shock waves which may be responsible for the death of the twister. This is probably the reason why tornadoes do not live for a long time.

(8) In deriving Bernoulli's equation for the outer region vertical velocities, friction, and the latent heat of condensation have been neglected. Because of these factors the model must be considered as a first approximation to a more exact one that may take them into consideration.

(9) It may finally be concluded that the proposed model may be found to give some plausible explanations for some of the observed facts about tornadoes. The model admits of various improvements and various checks. It is hoped that some exact quantitative observations may become available, and it may then be possible to check the results of the model, and to carry on the improvements, in a more intelligible way.

ACKNOWLEDGMENT

The author is greatly indebted to Professor James E. Miller of New York University for interesting him in the general problem of tornadoes, and for his numerous invaluable suggestions.

REFERENCES

1. A. J. Abdullah, "Cyclogenesis by a Purely Mechanical Process," *Journal of Meteorology*, vol. 6, No. 2, April 1949, pp. 86–97.
2. A. J. Abdullah, "On the Dynamics of Hurricanes," *Meteorological Papers*, vol. 2, No. 2, New York University, New York 1953, pp. 1–24.
3. E. M. Brooks, "Tornadoes and Related Phenomena," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 673–680.

4. D. Brunt, "Dynamics of Revolving Fluid on a Rotating Earth," *Proceedings of the Royal Society*, Series A, vol. 99, 1921, pp. 397–402.
5. D. Brunt, *Physical and Dynamical Meteorology*, 1st ed. Cambridge University Press, London, 1934.
6. E. J. Fawbush, R. C. Miller, and L. G. Starrett, "An Empirical Method of Forecasting Tornado Development," *Bulletin of the American Meteorological Society*, vol. 32, No. 1, January 1951, pp. 1–9.
7. E. J. Fawbush and R. C. Miller, "The Tornado Situation of 17 March 1951," *Bulletin of the American Meteorological Society*, vol. 34, No. 4, April 1953, pp. 139–145.
8. S. D. Flora, *Tornadoes of the United States*, University of Oklahoma Press, Norman, Okla., 1954.
9. S. Goldstein, Editor, *Modern Developments in Fluid Dynamics*, vol. 1, Oxford University Press, 1938, 330 pp.
10. B. Haurwitz, *Dynamic Meteorology*, McGraw-Hill Book Co., New York, 1941.
11. L. Howarth, Editor, *Modern Developments in Fluid Dynamics: High Speed Flow*, vol. 1, Oxford University Press, 1953, 475 pp.
12. W. Lewis and P. Perkins, "Recorded Pressure Distribution in the Outer Portion of a Tornado Vortex," *Monthly Weather Review*, vol. 81, No. 12, December 1953, pp. 379–385.
13. L. M. Milne-Thomson, *Theoretical Hydrodynamics*, 2nd, Ed., MacMillan Co., New York, 1950, 600 pp.
14. H. Newstein, "Tornado-Pressure Jump Line Situation of March 18, 1954," *Monthly Weather Review*, vol. 82, No. 3, March 1954, pp. 255–256.
15. Lord Rayleigh, "On the Dynamics of Revolving Fluids," *Proceedings of the Royal Society*, Series A, vol. 93, 1916, pp. 148–154.
16. H. Stommel, "Entrainment of Air into a Cumulus Cloud," *Journal of Meteorology*, Vol. 4, No. 3, June 1947, pp. 91–94.
17. M. Tepper, "On the Origin of Tornadoes," *Bulletin of the American Meteorological Society*, vol. 31, No. 9, November 1950, pp. 311–314.

Weather Notes

Editorial Note.—Many years ago the *Monthly Weather Review* published detailed eyewitness accounts of exceptional storms. These accounts both enrich the meteorologist's knowledge of storms and provide him with particular details that cannot be found elsewhere. Because such information bears directly upon questions the meteorologist must attempt to answer about weather phenomena (for example, the identification of storms as tornadoes), and because the information has potential value in both the research and service programs of the Weather Bureau, publication of eye-witness accounts of exceptional storms and other meteorological phenomena is being resumed in this issue. These accounts will appear from time to time under the heading "Weather Notes."

THE STORM AND TORNADOES OF MARCH 3, 1955

On March 3, 1955 thundersqualls developed to the west of Chicago and swept east-southeastward over Chicago, Ill., Gary, Westville, and on beyond Fort Wayne, Ind. At the eastern end of this path the storm struck after dark, but elsewhere the storm itself produced nearly the darkness of night, and even autoists were obliged to turn on headlights. Hail accompanied this storm over much of its path. The stones averaged nearly ¼ inch in diameter and barely covered the ground, but in some places stones were as large as golf balls and covered the ground, and inflicted much damage. Tornadoes were observed in this storm. Damage typical of tornadoes was inflicted at various places along the path of this storm, though at some of these places no one reported seeing a funnel cloud. To be sure the terrifying nature of the storm was such as to send most potential observers to cover in basements, and the darkness may have been a factor in obscuring funnels that may have occurred.

In Chicago the main features were hail and extreme darkness, with the height of the storm at about 1515 to 1530 CST. The storm was preceded by mammatus cloud formation. During the storm strange colored casts were observable, varying from greenish purplish to orange, such as is often associated with the more violent convective storms and tornadoes. Wind was not a serious factor in Chicago. Midway Airport reported a peak gust of 38 mph, while the University of Chicago reported one gust to 42 mph. Some minor wind damages were suffered, and it is likely that at some points in the city, higher speeds were reached. A pressure jump of over 0.12 inch was recorded at Midway Airport. Lesser jumps were observed at the University of Chicago and in the Loop. The pressure profiles during the storm at the three locations were vastly different, indicating the possibility of very small local circulations. The Meteorologist at Argonne National Laboratory in Lemont reported that the pressure change there was suggestive of tornadic activity in the vicinity. A man at 2315 E. 68 St., Chicago, reported that he observed a definite funnel cloud just east of straight south from his location, estimated at 5 to 10 miles away and apparently traveling eastward. This funnel was very dark and easily seen as it was backed by a lighter, yellowish or orange background. The bottom of the funnel was obscured by buildings, so that it could not be determined if it reached the ground, but its diameter at the lowest observable point was about one-tenth only of the diameter at the point where it was attached to the general cloud base. As the location of the funnel, as described, may have been in the Lake Calumet-Wolf Lake area, it might actually have reached the ground without being noted, as there is but little in the area that is subject to damage. It is perhaps more likely that the funnel did not reach the ground. As this funnel was observed by a man who had once experienced a severe tornado and also was seen by his wife, and as they were able to sketch and describe it so well, there is practically no doubt that it existed.

To the south of Chicago, in Park Forest, Ill., and along U. S. 30, hailstones the size of golf balls fell. Automobiles were dented and windows broken.

As the storm swept over Gary, Ind., it hit the eastern part particularly hard, especially in the Miller Beach and Odgen Dunes areas. Hail at Ogden Dunes was measured as large as 1¾ by 1½ inches, with many stones averaging 1¼ inches in diameter. Depth of stones on the ground was measured at 2½ inches, with drifts up to 10 inches deep. The pressure jump at the Duneland Observatory was only about 0.05 inch. Winds, however, were much stronger than recorded at Chicago, and reached a fastest mile averaging 58 mph from the northwest at 1601 CST. The five-minute maximum was 46 mph. Gusts to 60 mph were observed until the observer thought best to take refuge in the cellar. Peak gusts are conservatively estimated to have reached near 75 mph. The wind drove the hail nearly horizontally, so that many windows were broken. One house had 77 panes smashed. Greenhouses suffered serious loss. Much water damage resulted from hail and rain entering through broken windows of homes, and also much damage to roofs resulted from the wind and hail. Damage in the Ogden Dunes area was estimated at $150,000. Many automobiles were badly dented by hail. One woman in Gary was injured when her hand was cut by falling hailstone. As the above dollar loss is for only one 2-square mile area, and as the area of severe damage was 7 miles long and ½ to one mile wide, total damages in the Gary-Ogden Dunes area may be in excess of ¾ million dollars. (Revised figure is over $1,000,000 for Lake and Porter counties alone.)

The next community to be hard hit was the Village of Westville, at the intersection of U. S. 6 and Indiana 2. Here damages of $100,000 were suffered in an area about 5 miles long and about ½ mile wide. Within this area paths of severe damage were on the order of 50 to 100 feet in width, made by tornadoes which were observed by several people. The largest single loss was to a garage and contents at the mentioned intersection called West Point where a $50,000 loss was sustained, including loss of four trucks and four automobiles. Attendants and customers were unhurt, being in the office at the time, the only part of the building remaining intact. Debris from this building could be seen for a great distance, ½ mile or more to the southeast, and heavy metal parts were moved considerable distances. Though the general distribution of the debris did not indicate much rotation, the roof of this building was seen to have made a nearly complete circle after the building "exploded", landing on U. S. 6, only a few hundred feet from the original site. The force of destruction and nature of the damage were definite indications of a tornado, as well as the fact that a straight wind could not have reached this building without damaging other nearby and less substantial buildings. Many trees and one shed were destroyed within two miles to the west of this garage along U. S. 6, though the major area of damage was eastward from this point, in an area about 3 miles to the east.

(Continued on p. 98)

THE WEATHER AND CIRCULATION OF APRIL 1955[1]

Another Cold Month in the West

ARTHUR F. KRUEGER

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

1. TEMPERATURE AND CIRCULATION

During April 1955 subnormal temperatures continued for the fifth consecutive month in the western third of the nation. Negative departures as large as 4° F. extended from border to border with an extreme departure of 9° F. occurring in central Oregon (Chart 1B). As a result this month was one of the coldest Aprils on record in the Pacific Northwest, where temperatures were more characteristic of March than April. On individual days minimum temperatures dropped as low as 24° F. at Prescott, Ariz., 28° at Medford, Oreg., and 31° at Fresno, Calif. Frosts accompanying these cold spells were particularly damaging, especially in the Sacramento Valley of California.

This unusually cold weather resulted from the frequent influx of cold fresh maritime Polar air masses with a short fetch from the Gulf of Alaska which were driven inland by the circulation around a stronger than normal upper level anticyclone in the eastern Pacific (fig. 1). The abnormal strength of this onshore flow is indicated by the large anomaly gradient between the +260-ft. center near 40° N., 160° W. and a −220-ft. center in the Gulf of Alaska (fig. 1). Average wind speeds at the 700-mb. surface ranged from 17 m. p. s. over the Pacific to 10 m. p. s. across the west coast (fig. 2A), which represented speeds from 8 to 6 m. p. s. above normal (fig. 2B). The unusual coldness of these air masses is apparent from figure 3 where a negative thickness anomaly (1000–700 mb.) of more than 100 ft. covered Alaska, the northeast Pacific, and the Pacific Northwest.

While cold weather in the West during March persisted into April, this was not so in the Northern Plains, Great Lake States, and the Northeast. Here subnormal temperatures of March gave way to abnormally warm temperatures during April. In Minnesota, for example, the temperature anomaly changed from −8° F. in March to +8° F. in April. This strong warming accompanied a large increase in height of the 700-mb. surface over Hudson Bay, the Northern Plains, and Great Lakes as successive blocking waves influenced the area, resulting in a positive 700-mb. height anomaly of 290 ft. (fig. 1) and positive sea-level anomaly of 8 mb. in northeastern Canada (Chart XI and inset). These anomalies, in turn, were accompanied by a strong southerly anomalous component of flow having a long fetch from the lower Mississippi Valley north-northwestward into the Arctic.

Monthly mean temperatures also averaged above normal in southern United States as a result of prevailing southerly flow at sea level (Chart XI) and above normal heights of the 700-mb. surface (fig. 1). Afternoon temperatures during the month rose into the 90's as far north as Chattanooga and to 102° F. in the Rio Grande Valley.

2. PRECIPITATION

Precipitation accompanying the maritime invasions of the western States was unusually abundant, particularly in Washington and Oregon, where monthly amounts as high as 14.33 inches were reported (Charts II and III). This precipitation was distributed over a large part of the month with Portland, Oreg., for example, reporting 22 days with measurable rain, the second highest on record for April. More than twice the normal amount fell in eastern Oregon where Burns experienced 17 days with 0.01 inch or greater as compared with an average of about 4 days for the month. Furthermore, during the last 15 days of the month at least a trace of precipitation occurred on every day at Burns. In California the first heavy rains since January ameliorated the drought conditions that had developed. Some of the interior regions reported late season snowfalls. Salt Lake City, for example, received an April record fall of 12.8 inches early in the month and 5 inches more later on.

Important, though not independent, factors relating this precipitation to the monthly circulation were: (1) cyclonically curved flow occurring in connection with the mean trough along the coast, (2) below normal 700-mb. heights, (3) stronger than normal onshore flow of Pacific maritime air masses with forced ascent over the mountains, (4) frequent cyclonic activity at sea level (Chart X).

Precipitation in the Northern Plains was associated with a mean trough to the lee of the Rockies accompanied by below normal sea level pressures and 700-mb. heights (Chart XI and fig. 1). The accumulated amounts varied from about a half inch in the Dakotas to 4½ inches in Montana. Storminess responsible for this precipitation

[1] See Charts I-XV following p. 101 for analyzed climatological data for the month.

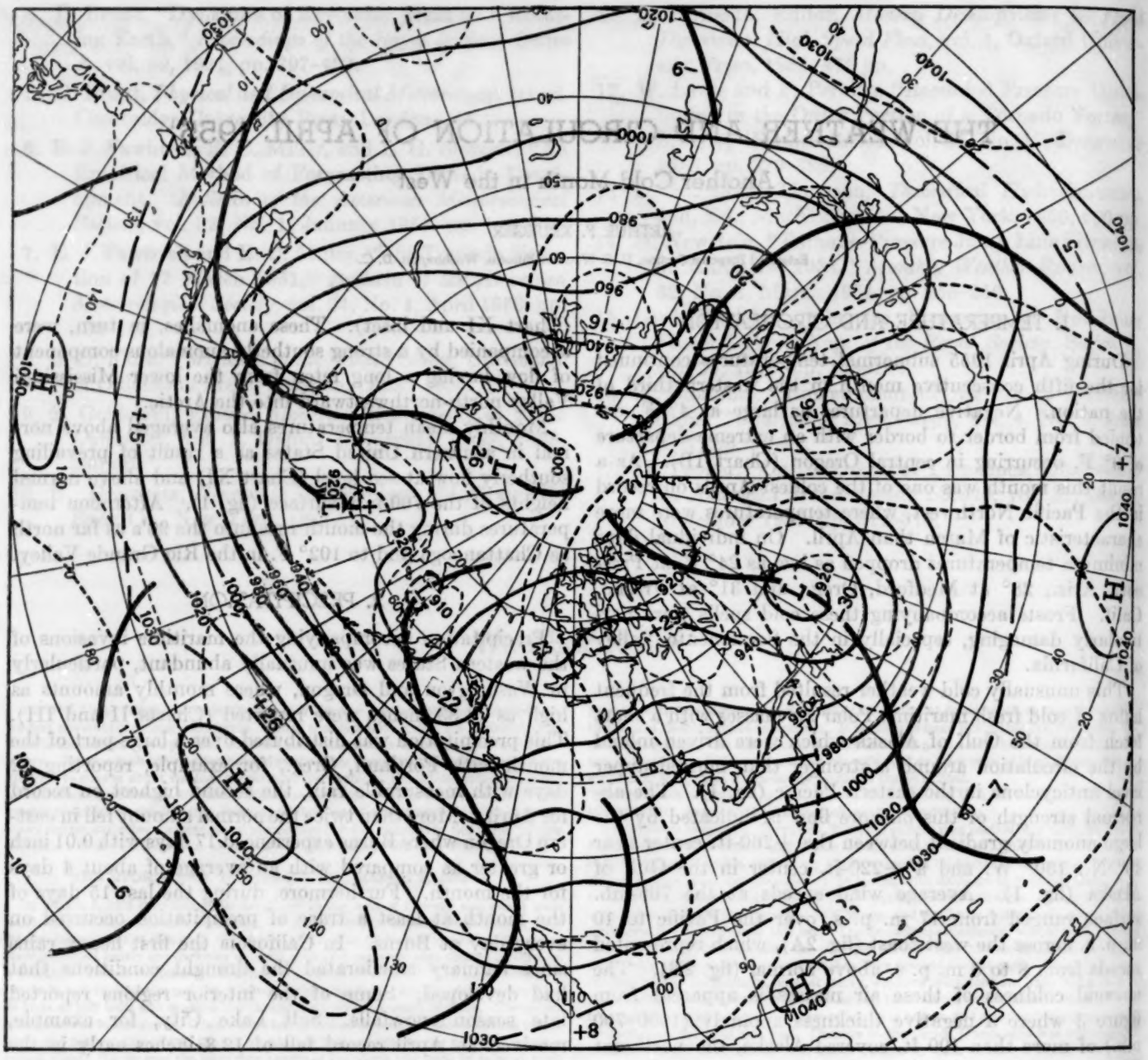


FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for April 1955. Important features for North American weather were the troughs in the west with below normal heights and the ridge in the east with blocking activity in northeastern Canada.

was frequent (Chart X) and displayed a tendency toward a 4-day periodicity, especially during the latter half of the month. Considering the number of storms, the amounts of precipitation in the Dakotas appear surprisingly small. While precipitation in the Dakotas was much less than in Montana, it was more evenly distributed throughout the month. For example, Fargo with a total of only 0.48 inch experienced 10 days of measurable precipitation as contrasted with Billings, where about nine times as much accumulated (4.42 inches) over only 6 days. In fact, by April 4 Billings had already received 93 percent of its monthly total.

Drought conditions continued in the Southern Plains, further depleting the already deficient soil moisture. This dryness was essentially in the nature of a "rain-shadow" caused by strong flow of Pacific air over the southern Rockies, where average wind speeds were 2–4 m. p. s. stronger than normal (fig. 2A, B). In this area the mean jet was considerably south of its position during March. This southward displacement was associated with a strong

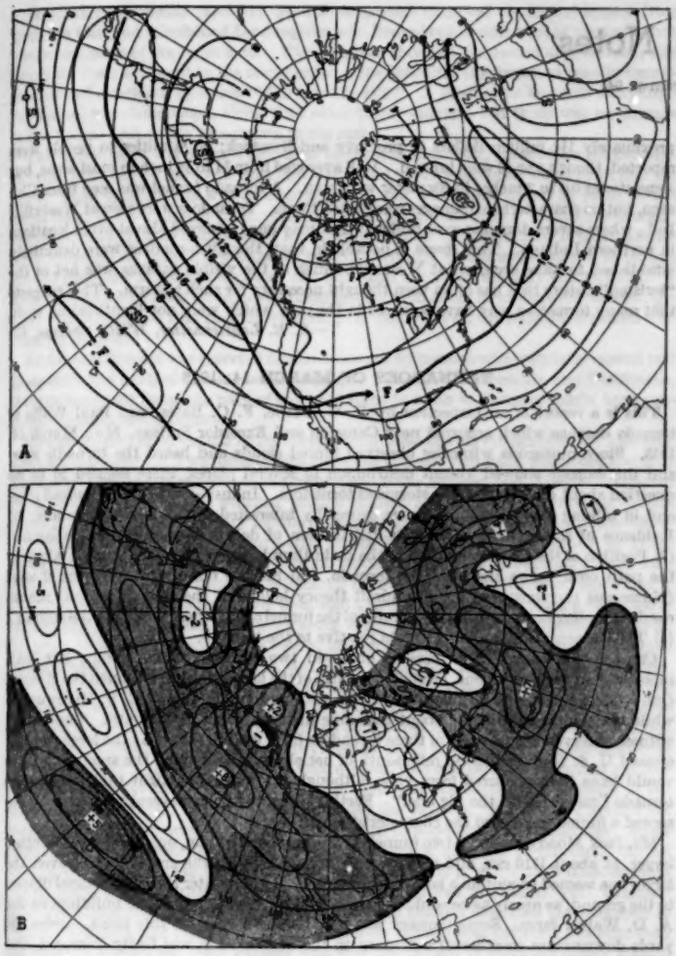


FIGURE 2.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for April 1955. Solid arrows indicate position of mean 700-mb. jet stream which was situated south of its normal position in the United States.

northwest-southeast tilt of the trough off the west coast (fig. 1) as momentum was periodically transferred southward.

The heaviest precipitation in the country occurred over the Southeast, where amounts of 17.69 inches fell at Mobile, Ala., and 12.29 inches at Memphis, Tenn. Most of the rainfall at Mobile occurred on the 13th when 13.36 inches or 75 percent of the monthly total was reported. At Memphis, however, the rainfall was more uniformly distributed. These rains represented, on the one hand, relief from drought along the Gulf Coast, and, on the other hand, a continuation of the rainy spell that characterized March in the northern part of these States and in Tennessee. Moisture for this precipitation was carried onshore from the Gulf of Mexico at low levels (Chart XI), and probably released by the vertical circulations accompanying the mean jet stream in the South (fig. 2A).

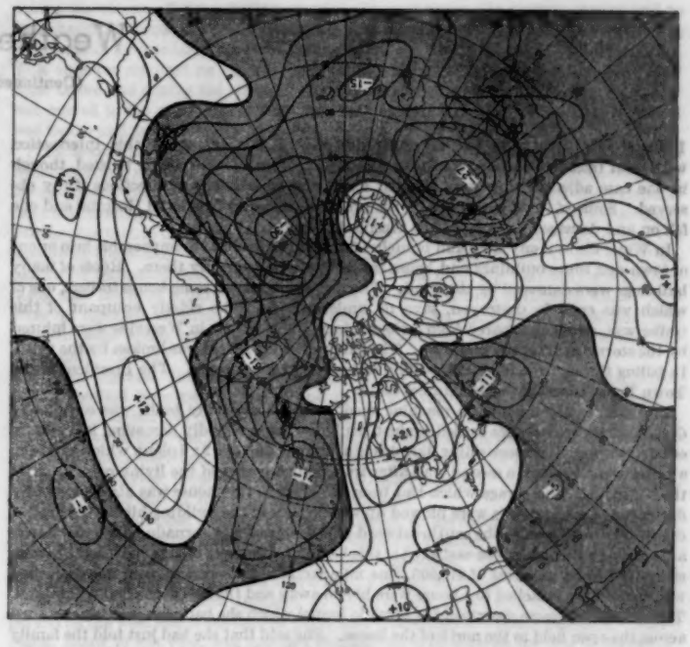


FIGURE 3.—Mean thickness anomaly (tens of feet) for the layer between 1000 and 700 mb. for April 1955. Isopleths are drawn at 50-ft. intervals and negative areas shaded. Unusually cold air in the northeastern Pacific was the source for the extremely cold weather in the West.

3. SOME CIRCULATION FEATURES IN OTHER PARTS OF THE HEMISPHERE

Off the east coast of North America heights of the 700-mb. surface were 300 ft. below normal, accompanying a 9,200-ft. closed low center south of Greenland. Storminess here was frequent throughout the month (Chart X), with most of the cyclones occurring north of the strongest band of winds at 700 mb. (fig. 2A) and the region of greatest cyclonic vorticity.

Bounding this region of subnormal heights was an elongated area of positive anomalies extending from northeastern Canada across Greenland, Iceland, and the British Isles to southwestern Europe. These positive anomalies were indicative of frequent blocking activity that characterized the circulation of this portion of the hemisphere. Anticyclonic activity over the British Isles was particularly well marked, resulting in a closed surface high center and strong 700-mb. ridge on the monthly mean (fig. 1), with predominantly sunny skies and dry weather.

East of the ridge a deep trough was located in central Europe with heights 200 ft. below normal. This was accompanied by extremely cold air, as indicated by the mean thickness anomaly of —270 ft. (fig. 3). Similarly very cold temperatures (—300 ft.) were indicated in northeastern Siberia, accompanying a low center in the Arctic and below normal heights throughout eastern Asia.

Weather Notes

(Continued from p. 94)

Paths of felled trees were seen on either side of U. S. 6 to the east of this intersection with most trees in an east to southeast direction. Trees were not badly twisted, though in one case adjacent trees were felled at about the most divergent directions of any observed. Some of these trees were on the property of Beatty Memorial Hospital and one fell on and damaged a house on the Hospital property.

In Westville so many trees and branches fell that the roads were impassable into or out of town and some buildings and house trailers were damaged by them. Roofs of many buildings were damaged by the wind. The tornado damaged some house trailers, one of which was entirely destroyed, save its undercarriage. The elderly occupant of this trailer was, strangely, spared from serious injury. Two others in Westville were injured by the storm; no fatalities occurred. The chimney of the school was broken by the wind. In falling through the roof, it caused an estimated $2,000 damage. The President of the Town Board reported seeing a funnel cloud.

One mile east from town a machine shed, very substantially built, was completely destroyed and parts were hurled against the house nearby, badly damaging it. Boards entered through the house siding like pins in a cushion, and one 2 x 6 plank which had been a rafter went through a second wall after traversing a corner of the living room to enter the bedroom. The garage which had been attached to this house was also completely destroyed. Large furrows were plowed up where parts of the building hit the earth, and debris was to be seen to the southeastward ¼ mile or more. A tornado path was observable through a woods to the eastward of this location. Damages to this one property were estimated to be in excess of $16,000. One mile farther east a carport and machine shed which had been attached to a house were blown away and the roof of the house damaged. The lady of the house described the tornado funnel which she had seen snaking eastward across the open field to the north of the house. She said that she had just told the family that they were safe as the tornado had passed and missed them, when their home was hit with the above mentioned damage. Apparently another funnel had approached unseen.

Total estimated damages in the Westville area ran to $100,000 or more. To summarize, the presence of tornadoes was definitely established, and it seemed almost necessary that there had been a family of small tornadoes to have caused the damages that were evident. Apart from the sightings of rotary action of debris and of funnels, and some variance of direction of tree felling, there was but little evidence of twisting action. Most trees were felled without twisting. This raises the question that it may not always be necessary to have a great amount of twisting evident in felled trees as a requisite for identifying a tornado. It is quite likely that many so called "straightline" winds in the past may actually have been tornadoes, and indeed, without careful investigation the damages at Westville might have been so attributed. The time of the storm at Westville was about 1615 to 1630 CST. The clock at the West Point Garage was stopped at 1617 CST. Hail in this area averaged about ½ inch, though the largest ones at West Point were reported to be nearly 2 inches in diameter.

The storm became ferocious again about 30 miles farther to the east-southeast, in the Teagarden-Lapaz area. A concrete block building located 3 miles west of Lapaz on U. S. 6, was demolished quite similarly to the garage at West Point, the explosive action suggestive of a tornado. As the building was not in use, no one witnessed its destruction. A tile-block garage and farm implement shelter on the Carl Bewley farm were badly damaged in their upper parts, typical of tornado damage. Also nearby a barn on the Roscoe Newcomb farm was lifted and partially crushed. A barn roof was demolished on the Ralph Bewley farm in this vicinity, on Tyner Rd., south of U. S. 6. Though no one reported having seen a funnel cloud, one farmer observed debris, dirt, and his wagon-bed picked up, moved, and the wagon-bed brought back again, in a violent twisting action. On the Kenneth Patterson farm on Quince Rd., one mile south of U. S. 6, roofs of the barn, two utility buildings, and the house were damaged. Press reports indicate that this occurred at shortly before 1800 CST. On the Karl Olson farm south of Donaldson a barn was struck by lightning and a cow killed. Half of a barn roof on the F. Lehman farm was demolished and two giant pine trees were snapped. The wind (tornado?) lifted the tree sections over the house with but minor damage to the house roof. A barn on the Roscoe Newcomb farm was lost as the timbers gave way; some damage was done to a car parked inside. This farm building was just east of the Lehman farm mentioned above, and on the south side of U. S. 6. Heavy damage was reported on other farms on Quince Road to the south of U. S. 6, including roofs of the house and barn on the Claude Grenert farm, and a steel granary which was blown away onto another farm. No estimate of damage was obtained, but from press reports and news pictures, it would seem that damages would surely exceed $30,000 in the Teagarden area.

Seventy miles farther east-southeastward, in eastern Fort Wayne, Ind., another area was struck with severe damage, estimated at $50,000. As it was dark when the storm struck, no one would have seen a funnel, and the occurrence of one is debatable from the evidence. Some evidence suggestive of such a funnel includes a 2 x 6 plank which had been picked up at a lunber yard and driven through the roof of the office building. Also, the area of damage was small, such as is often the case with such storms, being only about 500 feet wide and ¼ mile long. Five house trailers were overturned; one rolled about 100 feet. One woman was severely injured. Four or five others were less severely injured and required no hospitalization. One home was destroyed. Several thousand dollars worth of plywood was blown around at the lumber yard and the roof of the shed housing it was damaged. The Meteorologist in Charge of the Fort Wayne Weather Bureau made an investigation to see if anyone could be found who heard or saw definite evidence of a tornado. One woman said, "It sounded awful funny." However, the overall sound of the wind and hail was such that nothing definite could be determined in that manner.

In summary, this storm which swept from Chicago to Fort Wayne left damages of approximately 1¼ million dollars to property and livestock; no fatalities to people were reported, though 9 or 10 were injured. Hail averaged from ¾ to ½ inch in most areas, but some stones up to 2 inches in diameter were seen. A tornado funnel was seen from Chicago, but no characteristic damages were noted there. Tornadoes were seen at Westville, Ind., where severe damages were inflicted, and may have occurred also at other locations in northern Indiana. This storm is notable in that, though tornadoes were deninitely established to have occurred at Westville, much of the visible damage was not of the "twisted" nature that has often been thought necessary for such a storm. This suggests that many tornadoes may have occurred in the past which were not identified as such.

—*R. E. Lautzenheiser, WBO, Chicago, Ill.*

TORNADOES OF MARCH 14, 1955

This is a report of an inspection by R. G. Beebe, F. C. Bates, and Paul Waite of tornado damage which occurred near Cameron and Excelsior Springs, Mo., March 14, 1955. Since numerous witnesses observed funnel clouds and heard the tornadic roar, and the damage showed violent destruction in several places, there seemed to be no question about classifying these storms as tornadoes. In inspecting these damaged sites, and in talking to witnesses, we were especially interested in the following points: (1) Evidence of rotary motion through distribution of debris and eye-witness accounts. (2) Position of the tornado relative to the main thunderstorm cell. (3) Surface winds in the path both before and after the tornado. (4) Surface temperature change, if any. (Numerous proponents of the downdraft theory hold that the cold downdraft should result in cooling in the immediate vicinity of the funnel cloud where it reaches the ground.) (5) Time of occurrence of hail and rain relative to the tornado.

Cameron Tornadoes.—Two persons observed two distinct funnel clouds, but both reported that the smaller one, located just south of the large one, did not touch the ground. One witness was about ½ mile south of the path and 1 mile west of U. S. Highway 69, while the second person was about the same distance north of the path. The second witness observed the progress of these tornadoes from west to east. As the large tornado crossed U. S. Highway 69 (½ mile south of her observation point), the smaller tornado would have been obscured from view, although the witness thought that the smaller tornado "merged with the big one." Farther along the path, several persons both observed a funnel and heard the characteristic roar.

Mr. Jack Moody observed two funnels to the northeast of him, one small and the other larger, at about 1710 CST, and neither were in contact with the ground. However, the larger one seemed to contain a lot of dust and dirt. Seconds later the larger funnel dipped to the ground, as nearly as he could ascertain, just west-southwest of the buildings on the A. D. Walker farm. Some damage was noted along a fence at this point. Some 200 yards downstream (northeast) a granary on the Walker farm was badly damaged, and the debris scattered to the east-northeast for about 300 yards and directly along the tornado path as evidenced by broken tree limbs. No debris was noted to the north or south of the path. The Walker house, located some 50 yards to the southeast of the granary, was not damaged except that a brick chimney was blown off toward the north-northeast. Since a TV antenna was anchored to this chimney, this damage would seem to have resulted from strong wind. Three persons were in the house at the time and heard no roar. They observed no funnel, but did see whirling debris and dirt in the air north of the house at the time.

Some scattered slight damage to trees occurred over the path for about the next mile. Two sheds on the W. E. Middaugh farm (east-northeast of the Walker farm) were completely demolished, and debris, including boards and sections of the roof, were thrown to the north and north-northwest (left of the path) as much as 200 yards. About ¼ mile down the path, considerable damage was done to other buildings including the residence of the Middaugh farm. At this point, Osage orange trees, some 200 yards south of the apparent track, were badly damaged. Also, south of the track, weeds were blown against a woven wire fence (along a north-south line) from the west. The fence was packed with weeds and straw to a depth of about 6 inches and a height of 3 feet southward from the farm buildings to the Osage orange trees. Two trees on the northeast and southeast corners of the house had large branches broken off toward the south. Several windows in the house were shattered with the glass outside.

The path continued across the road (U. S. 69), evidently on an easterly course now, with scattered damage to trees. Considerable damage occurred on the Chester G. Curtis farm to buildings and trees. While a barn was badly damaged and large trees near the house were blown over, the house appeared untouched—all windows were intact. All debris seemed to be along a narrow (50-yard) path toward the east. Many orchard trees were blown over from the west or southwest. Mr. Curtis heard the roar while inside the barn which was badly damaged. Although 5 sheep were killed in this barn, Mr. Curtis escaped injury.

At the W. H. Potter farm (immediately to the southeast of the Curtis farm on south side of Missouri 121) large trees north of the house were blown eastward, the house was undamaged, and the major damage occurred to a garage just south of the house. A car inside the garage was overturned and badly damaged. Debris was thrown eastward.

At the Leonard Jones farm directly eastward from Potter's a small house was moved about 30 feet toward the southeast. Several small buildings were demolished and debris was scattered toward the east. A small fenced (woven wire) field just east of the buildings showed a packing of straw and weeds from the west along the north-south fence and a packing of weeds and straw from the north along the east-west fence. The only injury caused by the two tornadoes was to Mrs. Lois Jones, who was in a trailer home in their farm yard as it was overturned. Mrs. Jones suffered shock, bruises and abrasions.

Mrs. Harry Sockman (also Mr. Medille Sockman) observed the funnel approaching from the west and telephoned her daughter who lives about ¼ mile west of her and about 1 mile southeast of the Jones farm. The daughter then saw the funnel approaching, also heard the roar, and went to the storm celler. She described the funnel as exactly funnel-shaped and extending upwards "high into the sky." A shed, some 30 yards away from the house, was demolished, along with other minor damage, but there was no damage to the house. All debris was strewn to the east.

The buildings of the Steve Tully farm to the east-southeast, suffered severe damage. Several windows on the south were blown outward, and a lamp table was thrown into the yard. Most of the debris was thrown eastward, but with some debris 50 yards to the north (left) of the apparent path. Bessie Tulley left Cameron in a "heavy rainstorm," drove south on U. S. 69 until she saw the two funnels near the intersection of this highway with Missouri 121 (near the Middaugh farm). Here she waited until the two tornadoes moved eastward across the highway (69) and then she could see only one tornado. A little later (she could not estimate the time) she drove on to her farm some five miles to the east. She estimated that they drove 40 m. p. h. but, even so, the tornado remained well ahead of the car.

Additional damage was reported farther eastward by persons who were interviewed and these include reports of tornado occurrences near Kingston, Mooresville, and Chillicothe. If those were tornadoes, the path of the main tornado south of Cameron might have continued to these other localities.

Interviews and observations in connection with these storms brought out the following interesting points: (1) Two funnels were observed but only one track was noted and only one tornado was observed to reach the ground and cause damage. (2) The roar was heard by several persons. (3) A whirling motion of dust and debris was noted by several persons. (4) Evidence of rotary motion in damage or debris was noted at only the following three locations: *a*. Debris from a shed on the Middaugh farm was thrown up to 200 yards north and west of the original location while the tornado was following a track from about 240°; *b*. Two trees near the Middaugh farm were broken off toward the south; *c*. Debris on the fence of the Jones farm indicated a strong westerly wind along a north-south fence which covered an east-west fence along which debris was driven in from the north. (5) With these three exceptions *all* debris, broken trees, and branches indicated a strong westerly wind. (6) The path width was never wider than 250 yards and generally less. The length investigated was about 6 miles and perhaps was as much as 30 miles. Some "skipping" was noted throughout the length, although some of this could be a consequence of a track over open fields. (7) All witnesses stated that the main thunderstorm cell was to the north where rainfall amounts were generally given as 1 inch or more, starting about 2 or 3 miles north of the tornado track. One witness, who was perhaps in the best position of any, stated that the two tornado funnels were near the southwest quadrant of the thunderstorm cell. (8) No rain or hail preceded the tornado. Light rain ("settled the dust"; "less than a quarter inch." etc.) followed the tornado by about 10 minutes. Some hail ranging in size from ¾" to 1¼" followed the tornado by about 10 minutes. (9) All observers gave the time as either "around 5 o'clock" or 5:10 p. m. (10) Witnesses could not state definitely whether or not the funnels were attached to a cloud. (11) Thunderstorms preceded and followed the tornado. (12) All persons described the afternoon as "windy" but said that before and immediately after the tornado, the wind was light from the south or southwest. (13) Persons who saw the funnels or observed rotary motion could not describe the direction of rotation. (14) All persons who were in the vicinity of the funnel itself stated that they observed no noticable temperature change as the tornado passed by.

[Editor's note:—In addition to the above we have received two eye-witness accounts which follow. The first observer located the storm as 4 miles south of Cameron at Clinton School and thence eastward. He was located about 2½ miles north of the storm and about 1 mile east. He reported seeing funnel at 1710 CST hanging from the cloud base and touching the ground. Hail of ½ to 2 inches in diameter fell over a "large area" during the storm. Largest hailstones were observed before the storm's passage and to the left of its subsequent path. Excessive rain (1.1 inches in 10 min.) fell before and during the period of most intense winds and to the left of the path of maximum wind intensity. This observer reported no excessive lightning or thunder, but heard an unusual, loud noise before and during the storm's passage but after the heaviest rain when the storm had moved to the east. It sounded like "hail on farm buildings farther east though it was louder and more intense."

[The second observer reported the storm location as 8 miles southwest of Hamilton which is directly east of Cameron. At about 1700 CST he saw a funnel extending from the cloud base and touching the ground. It moved from west to east and had a counter-clockwise rotation. The pattern of debris was also counterclockwise. Hailstones three-fourths of an inch in diameter, fell over an area he estimated as 6400 square miles during the passage of the storm. The hailstones were largest after passage and to the left of the path. He estimated that two inches of rain fell in one hour, the heaviest period of rain being after the most intense winds and to the left of the path of maximum wind. This observer reported no unusual lightning but unusually loud and frequent thunder. No other unusual noises accompanied the storm. Both observers reported observing the storm until 1730 CST.]

Excelsior Springs Tornadoes.—The storm damage in and near Excelsior Springs evidently resulted from two tornadoes and possibly a third. The first occurred east of town and damaged five farm buildings along the County Line Road. One person who was interviewed observed the funnel and heard the characteristic roar at 1740 CST. Several barns and sheds were demolished and the debris lay in a straight line, apparently along the path. However, these sites were not investigated in detail. Also, there were reports of damage as far east as Rayville, 9 miles to the east.

The second, and most destructive tornado, struck in the center of Excelsior Springs at 1800 CST. The principal damage was to the Lambert Lumber Yard where the roof (160 feet long) was blown off and debris scattered to the south. Large pieces from this roof were carried two blocks away and over a 2-story school building. Some 35 windows of a motel across the street were damaged by flying debris. Two cars and a dump-truck, parked on the west side of the lumber yard, were overturned and badly damaged. A 2 x 6 plank, about 10 feet long, was rammed through the dual tires on the rear of the truck. After the storm, the truck was on its side with about 8 feet of the 2 x 6 extending vertically upward.

While the lumber yard was located near the center of the city, no other damage of consequence was noted except a plate glass window in a filling station was exploded outward and one stop sign was twisted off. Mr. Walter Armstrong, manager of the Lambert Lumber Yard, heard the roar which he identified as a characteristic of tornadoes (he had heard this roar on two previous occasions). One filling station attendant, near the the lumber yard, was reported to have observed the funnel itself. Light rain fell in the vicinity during the tornado and several persons reported that the dark thunderstorm clouds were to the north. Hail, diameter up to three-fourths of an inch, fell about 15 minutes after the tornado occurrence.

Another (possibly the same one as described above) storm occurred about 2 miles southwest of town around 1800 CST. This path was short and horseshoe-shaped, and the storm moved to the southeast. A garage and barn were smashed. There were no reports of a funnel or roar in this area; the information here was given by Marvin Crowley, a reporter for *The Daily Standard*.

Severe Local Storms forecast No. 50 was issued at 1210 CST this date and was as follows: ". . . most intense area along and 50 either side line from 30 west Topeka to Ottumwa, Iowa, with scattered tornadoes expected this area from 1400C to 2200C. . . ." This forecast was known to most of the persons interviewed and several expressed their appreciation of the Weather Bureau's "twister forecasts." Protective measures were generally to keep watching for unusually dark thunderstorms or funnel clouds and take cover after the funnel was sighted.—*Robert G. Beebe, SELS Center, WBAS, Kansas City, Mo.*

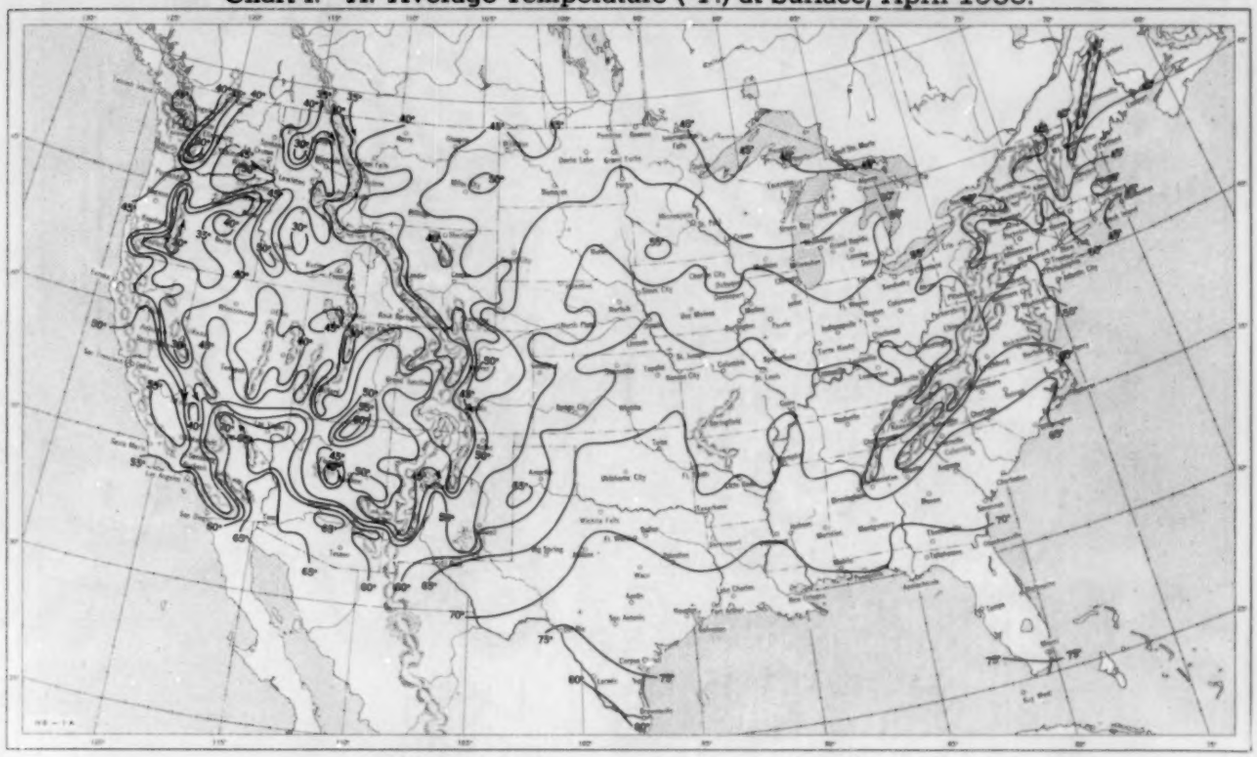
CORRECTION

MONTHLY WEATHER REVIEW, vol. 83, No. 3: In table of contents on front cover, author of "The Weather and Circulation of March 1955" is Jay S. Winston.

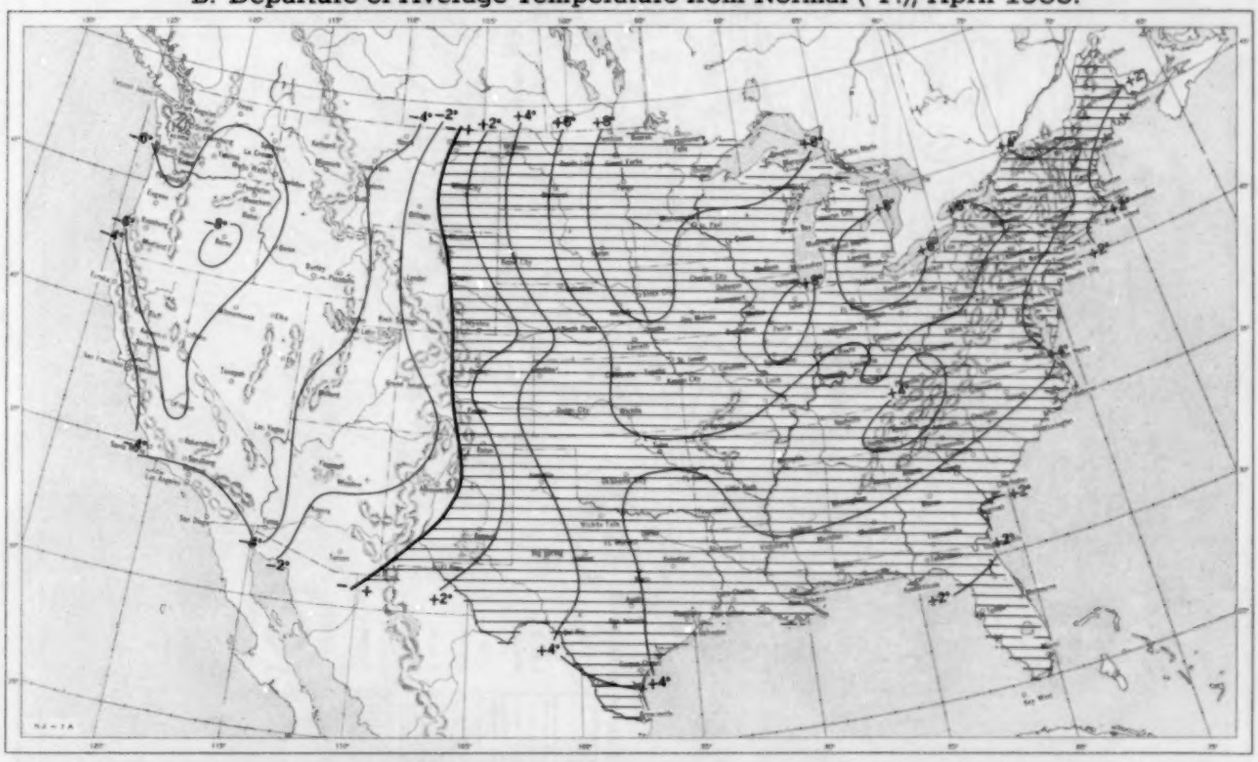
345634—55——2

U. S. GOVERNMENT PRINTING OFFICE: 1955

Chart I. A. Average Temperature (°F.) at Surface, April 1955.

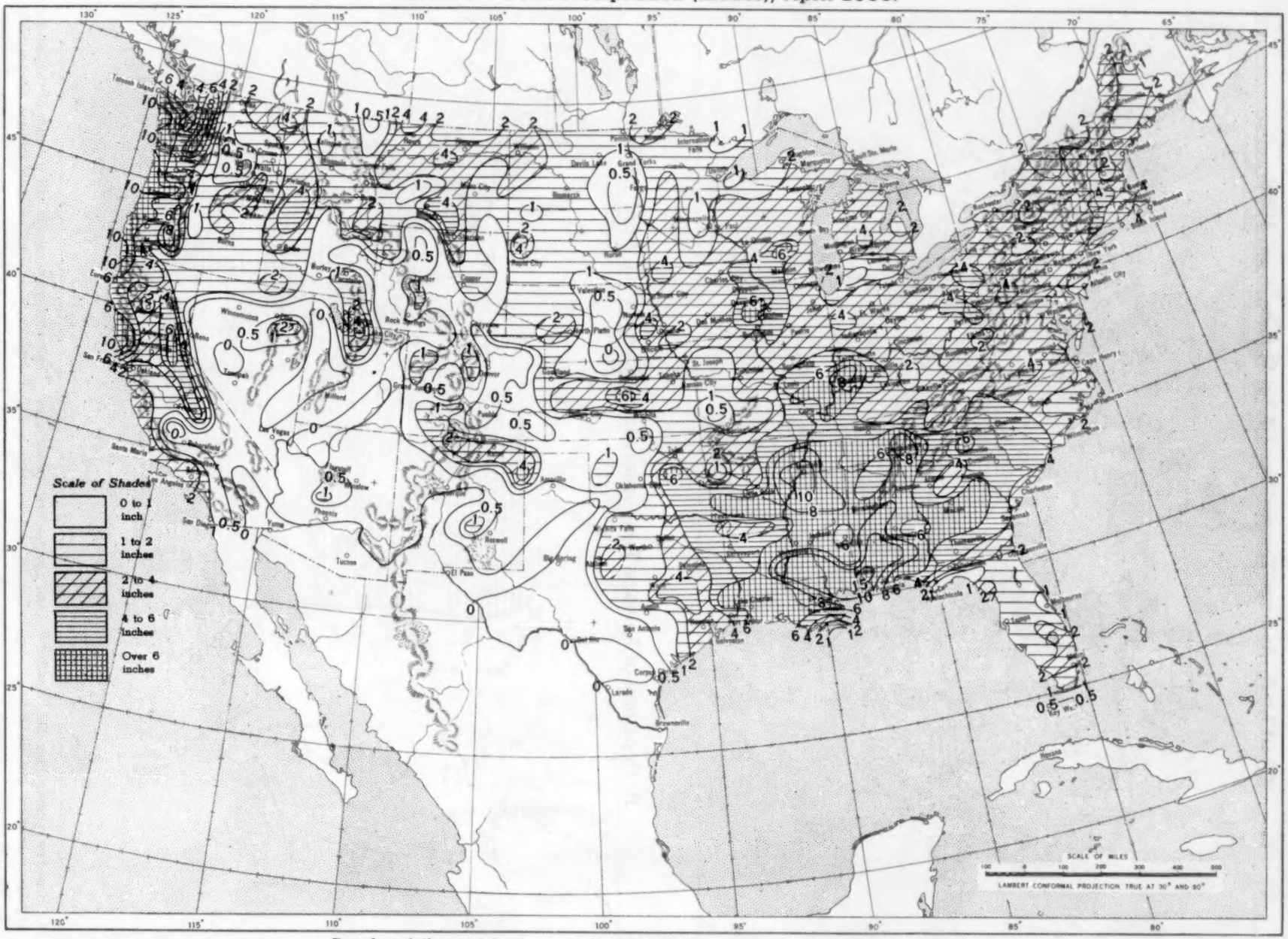


B. Departure of Average Temperature from Normal (°F.), April 1955.



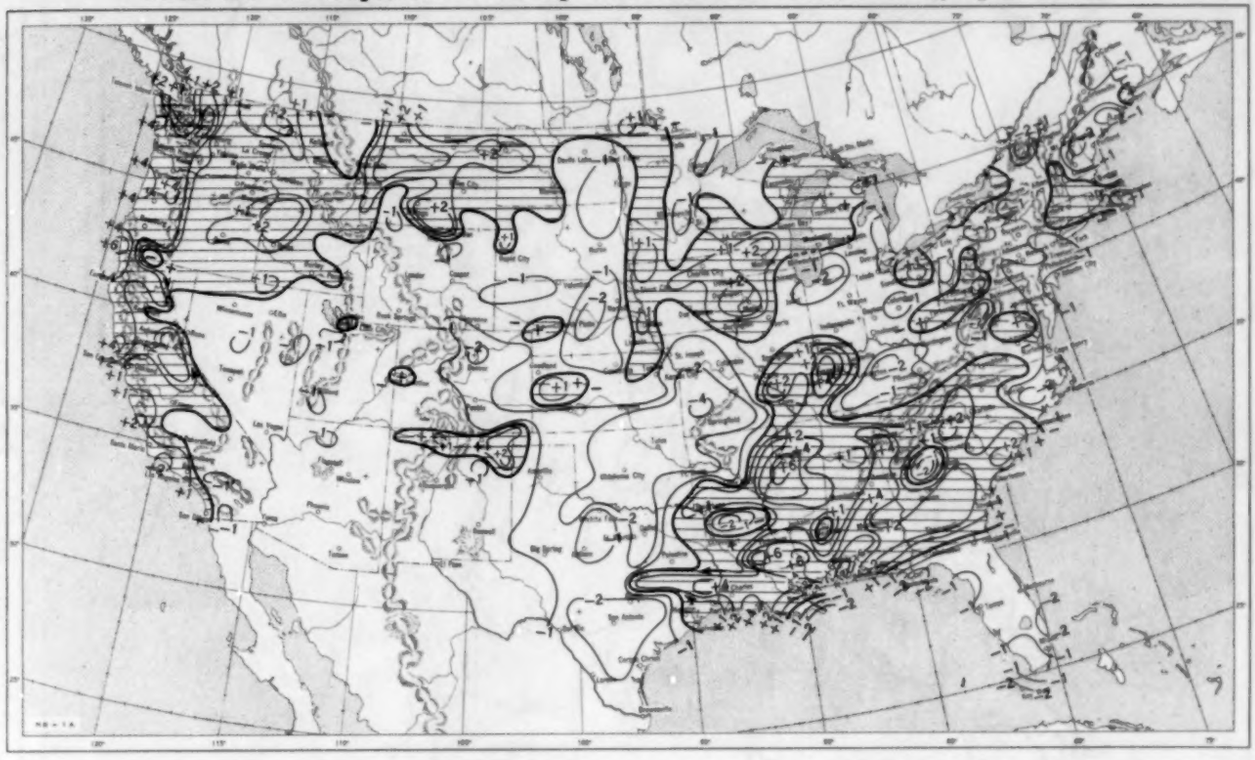
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), April 1955.

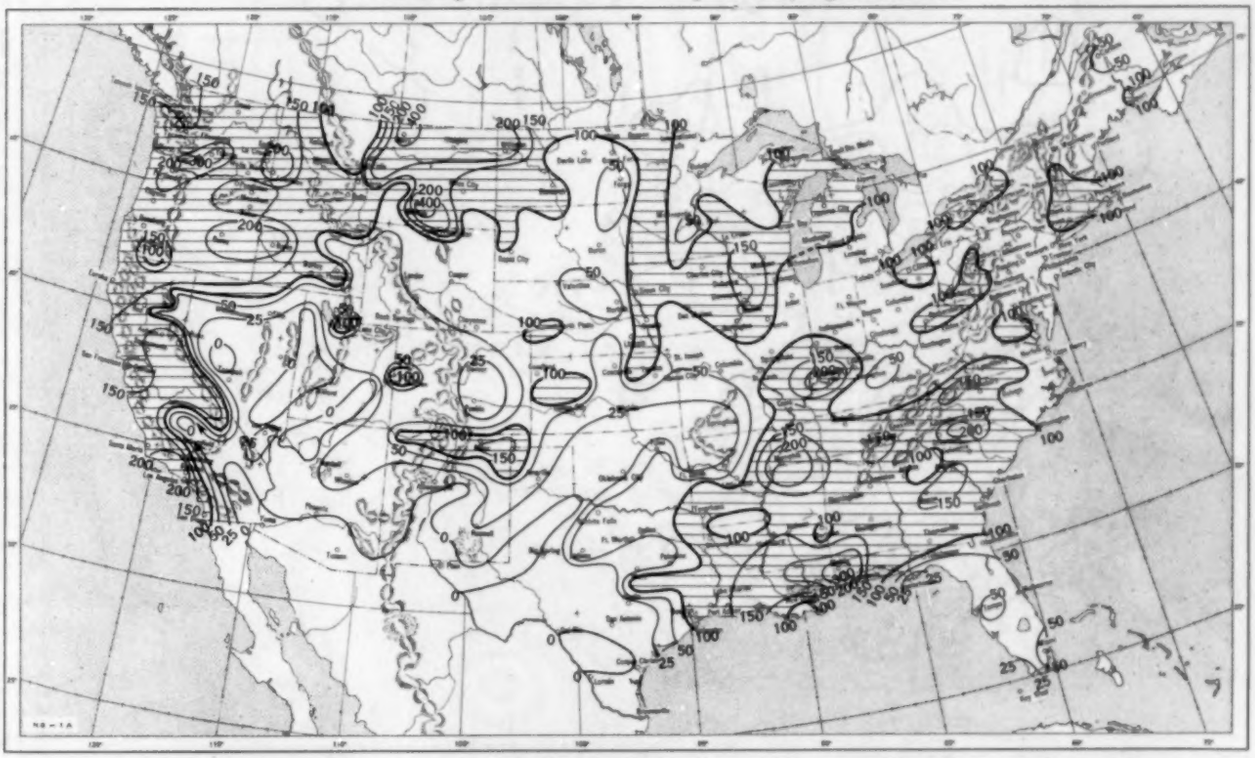

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), April 1955.

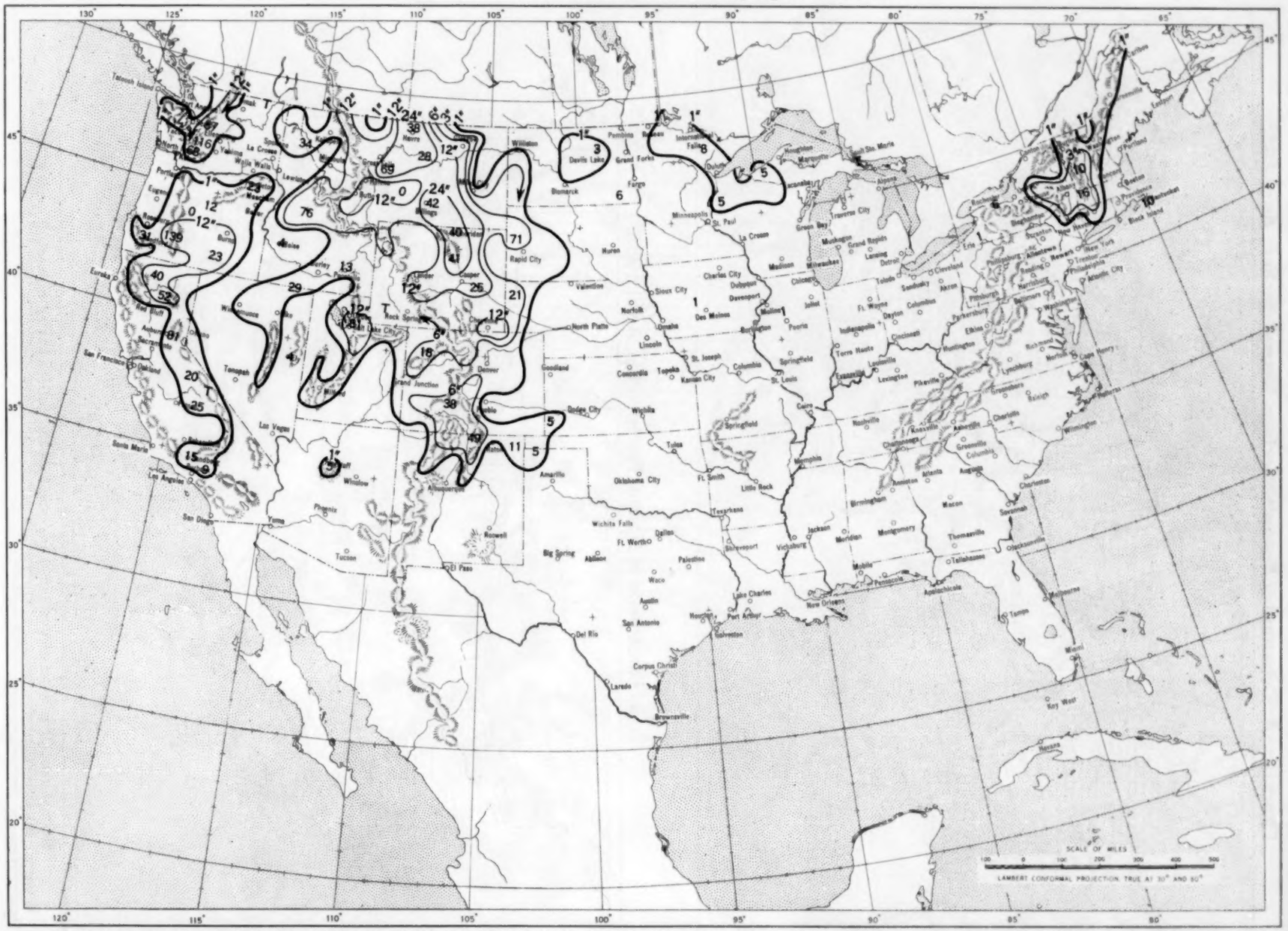


B. Percentage of Normal Precipitation, April 1955.



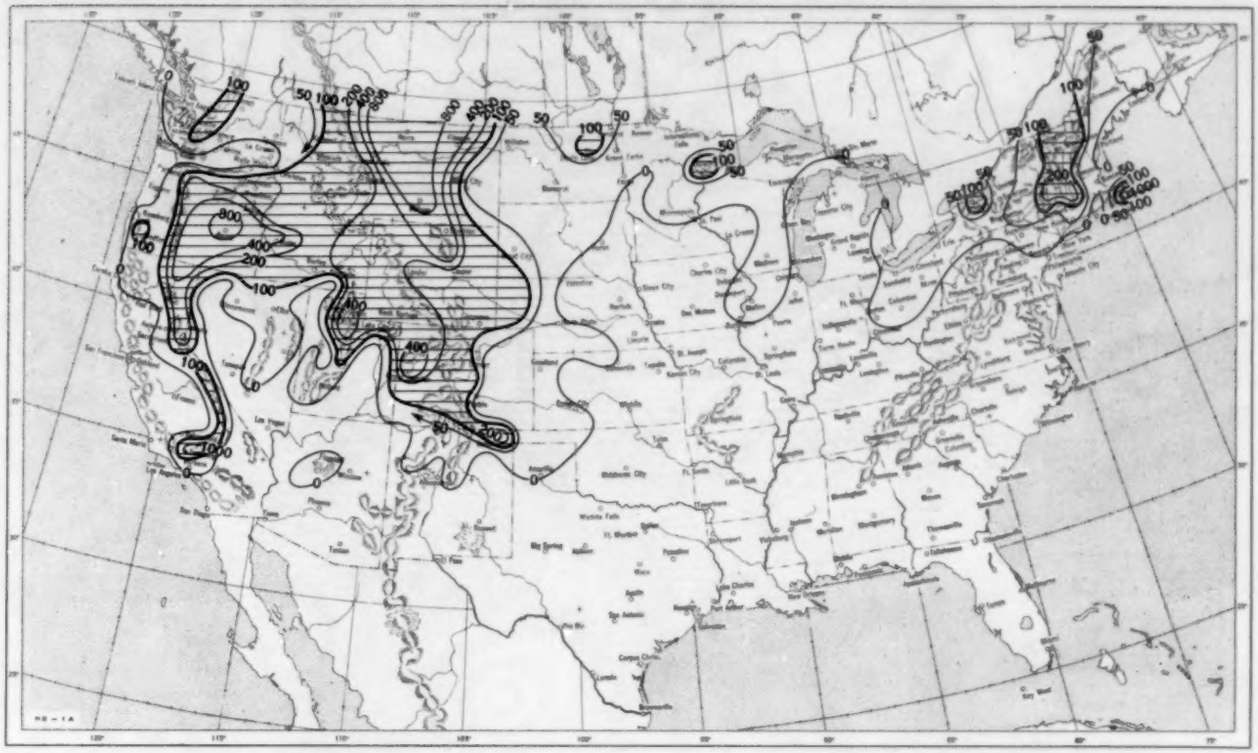
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), April 1955.

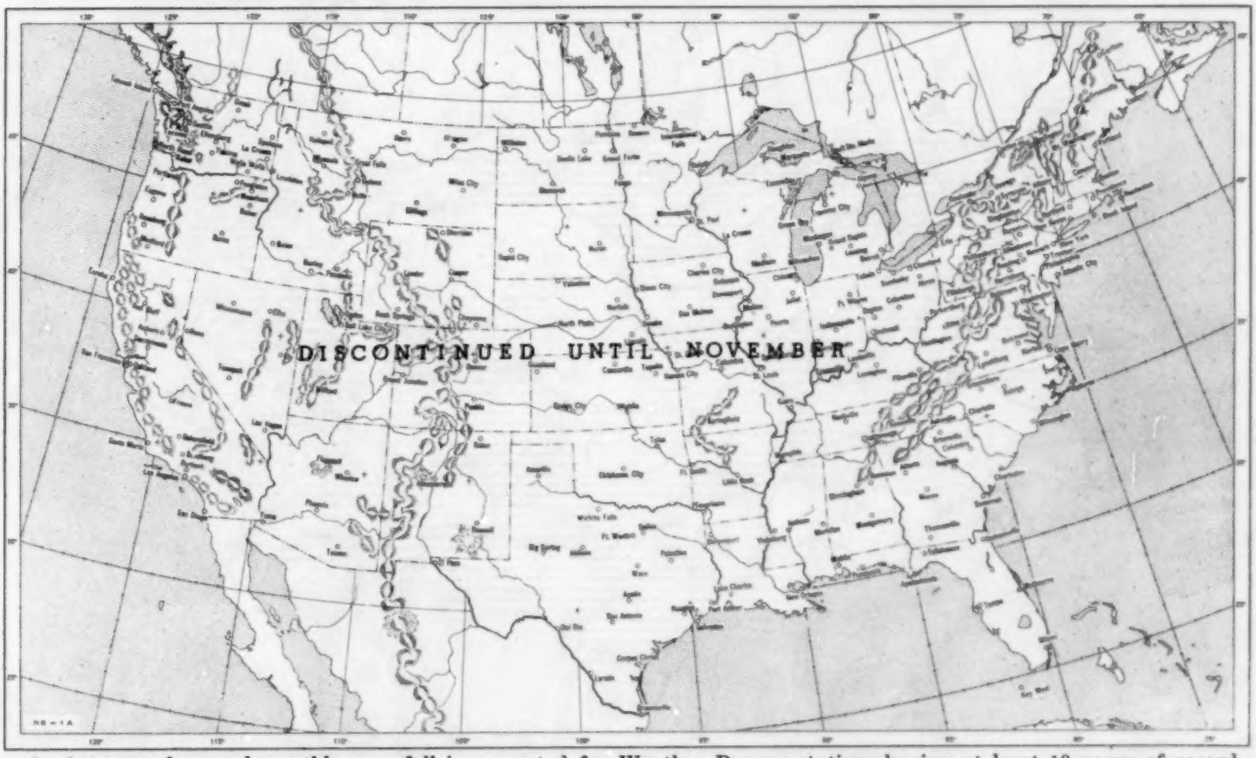


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, April 1955.

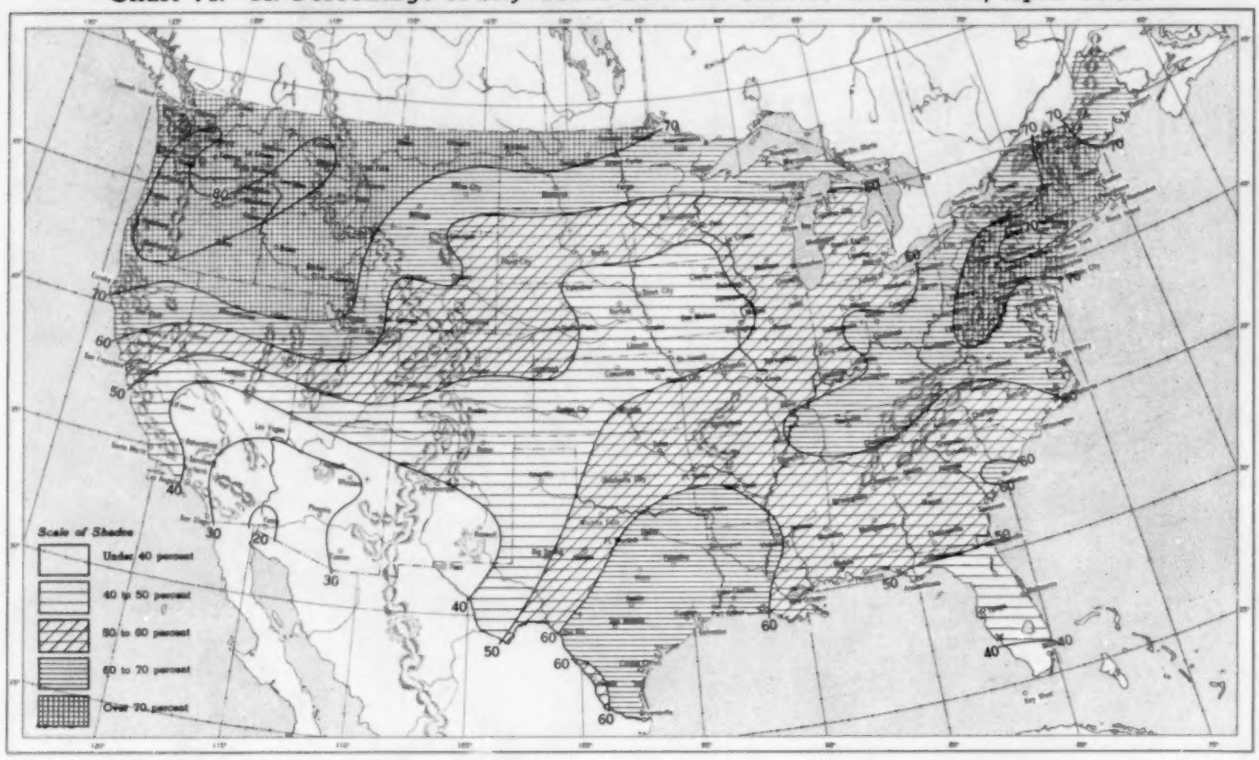


B. Depth of Snow on Ground (Inches). 7:30 a. m. E.S.T., April 25, 1955.

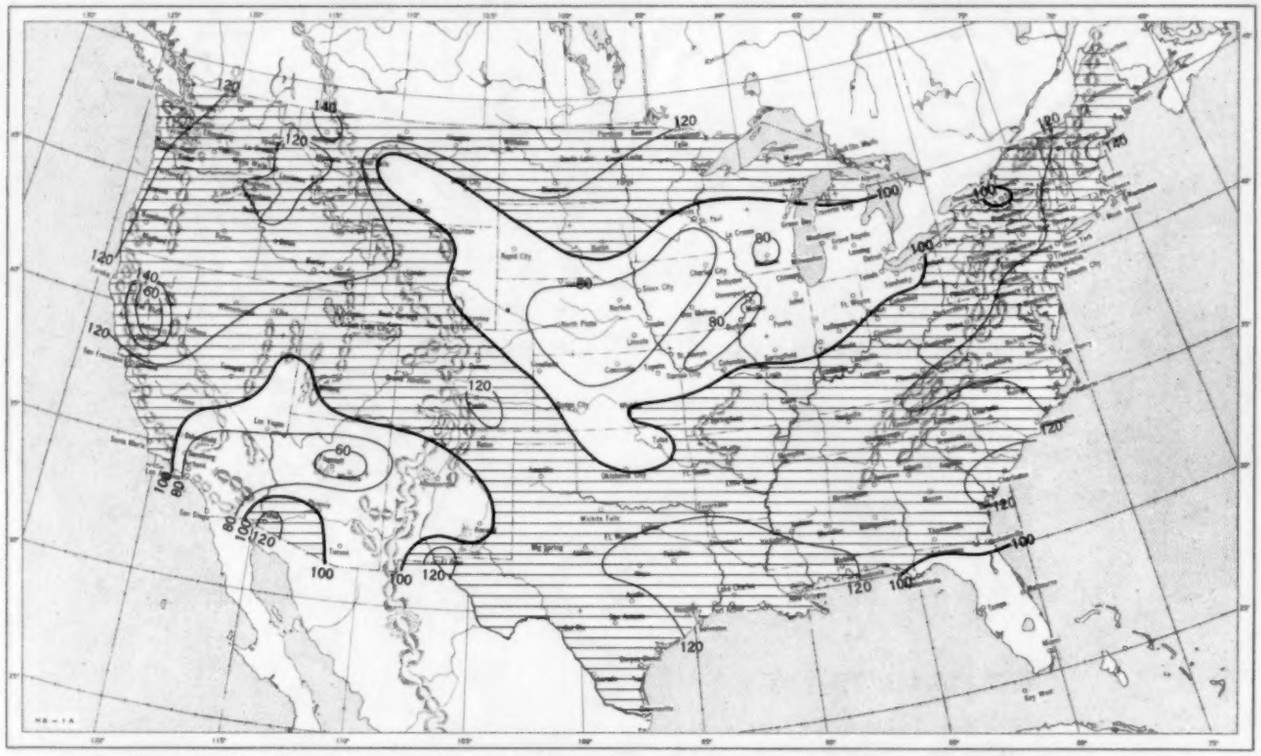


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E.S.T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, April 1955.

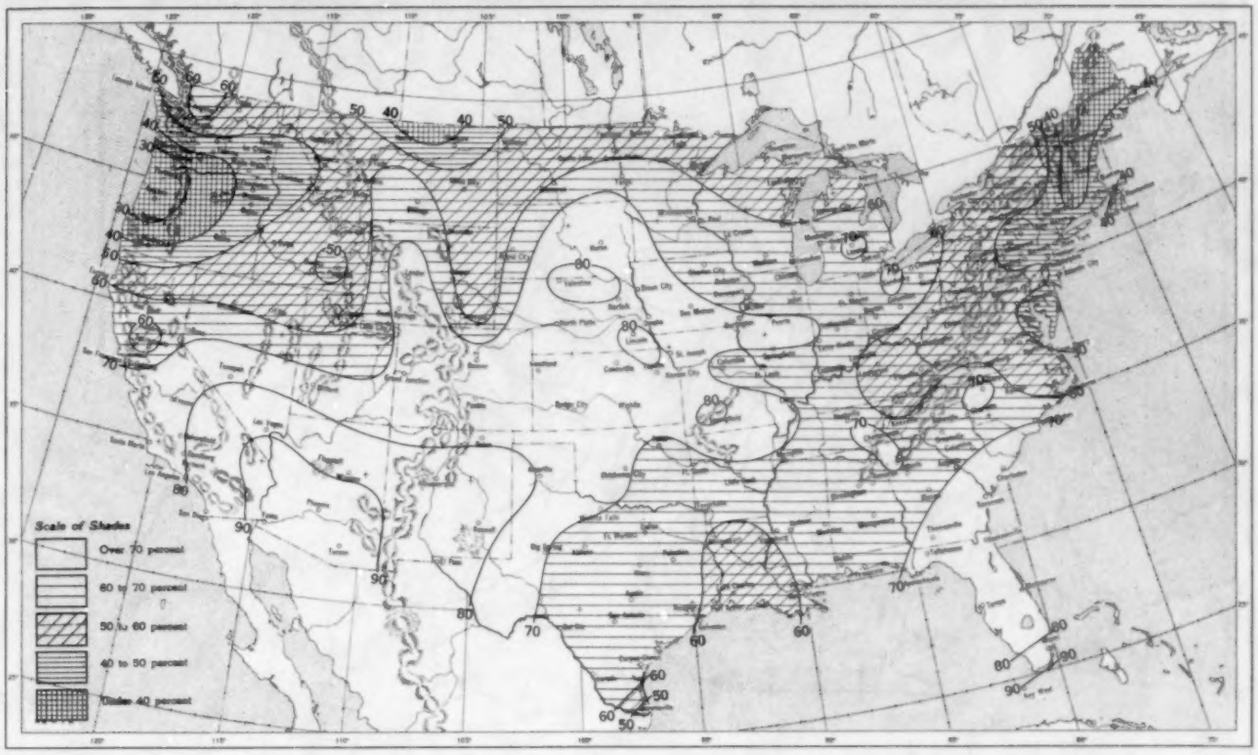


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, April 1955.

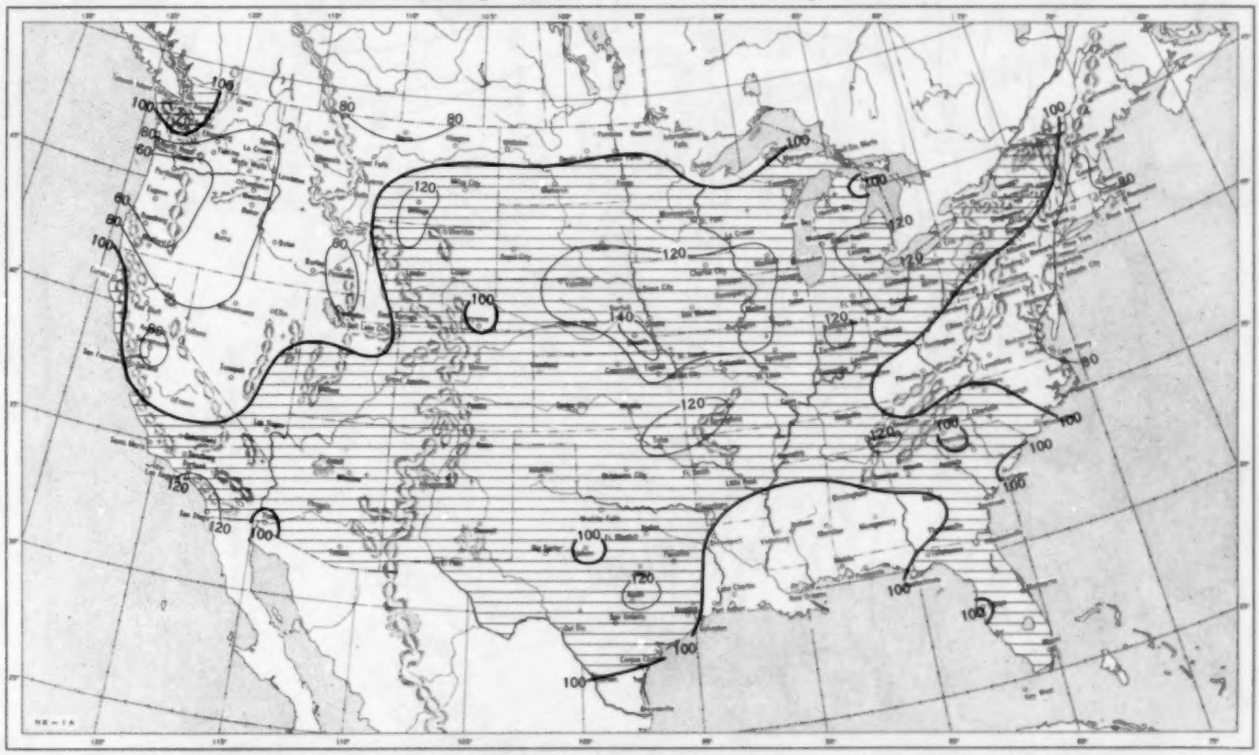


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, April 1955.



B. Percentage of Normal Sunshine, April 1955.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, April 1955. Inset: Percentage of Normal Average Daily Solar Radiation.

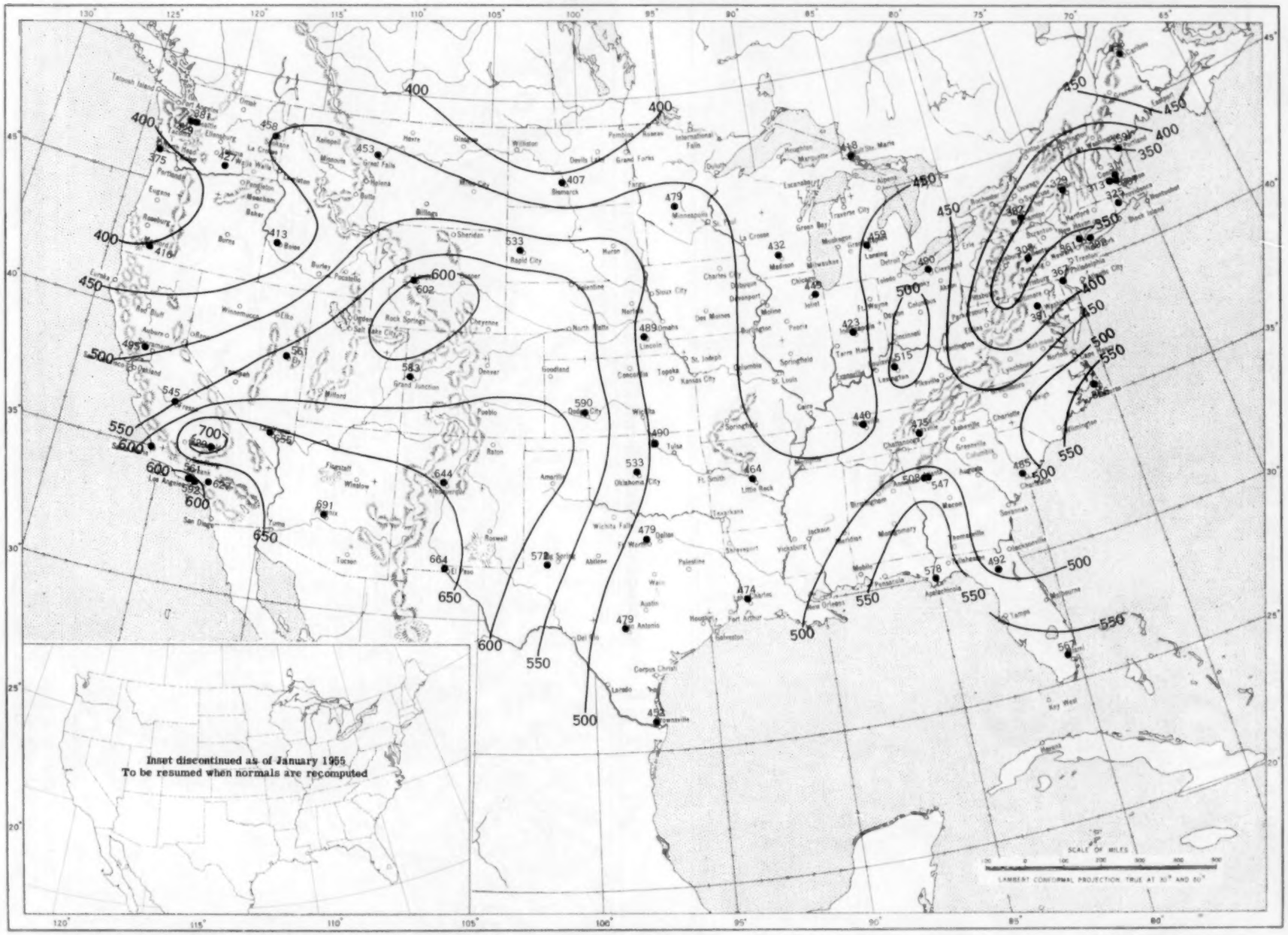
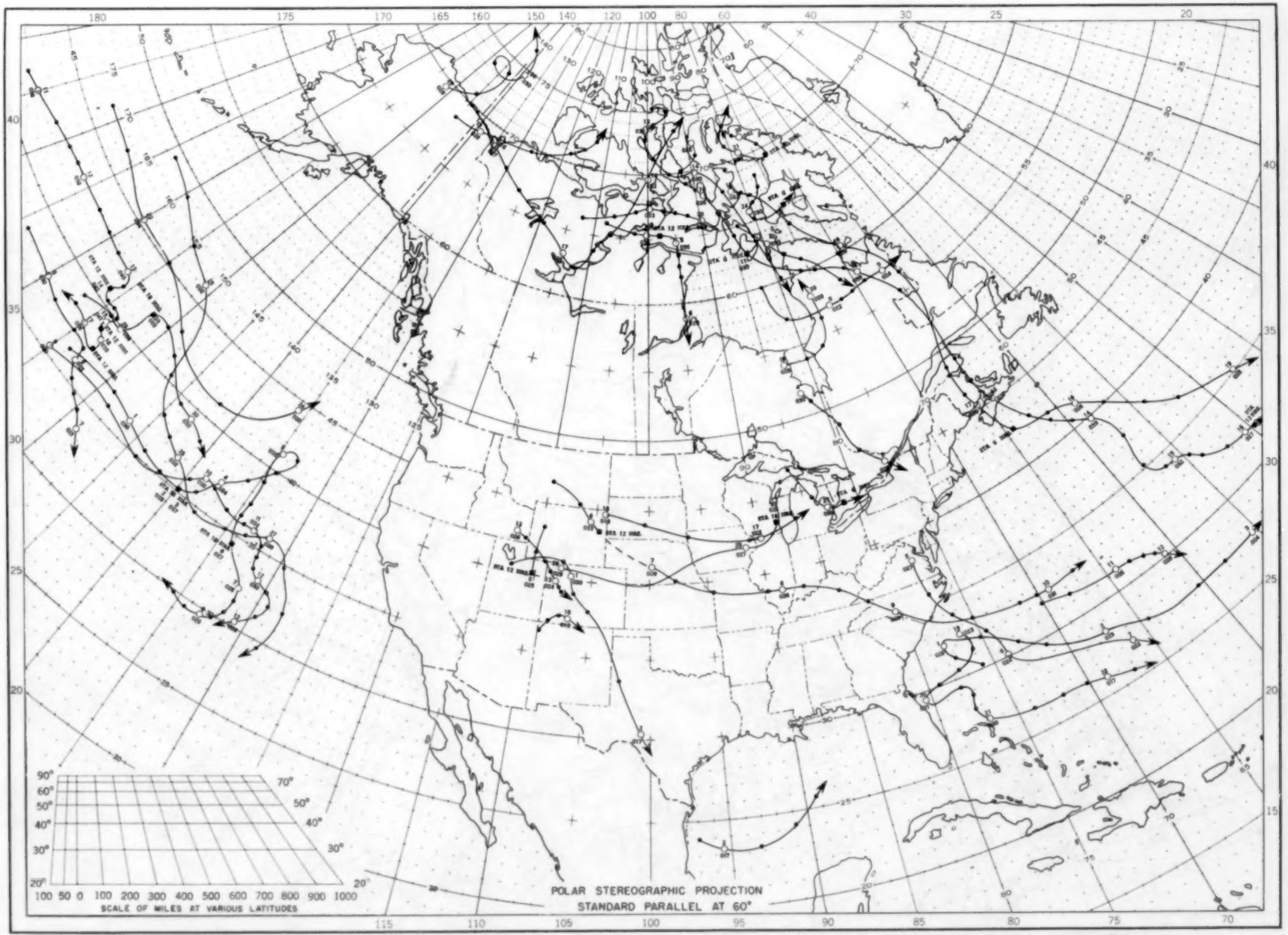

Inset discontinued as of January 1955
To be resumed when normals are recomputed
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 33° AND 45°

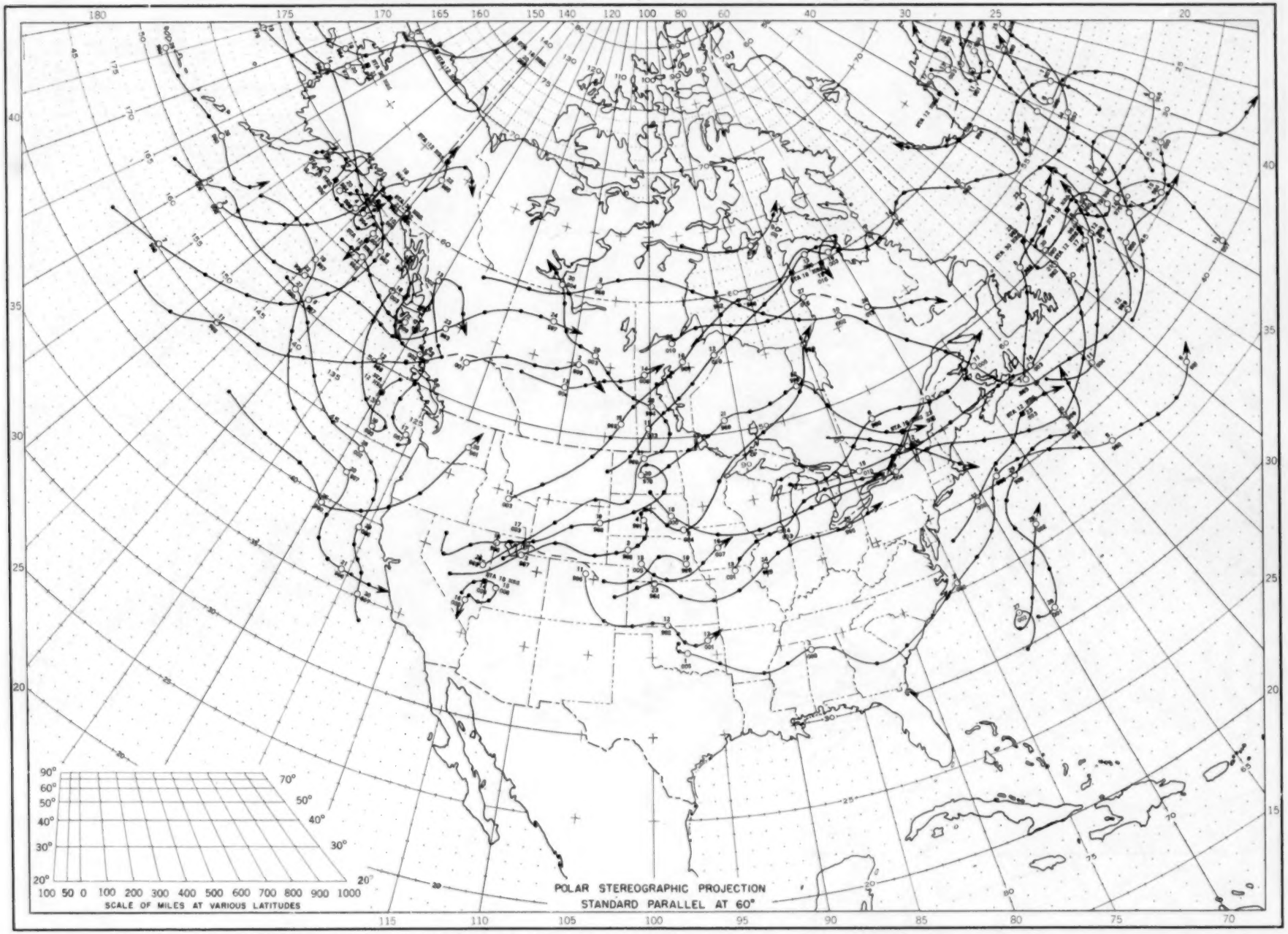
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, April 1955.


SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000
POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

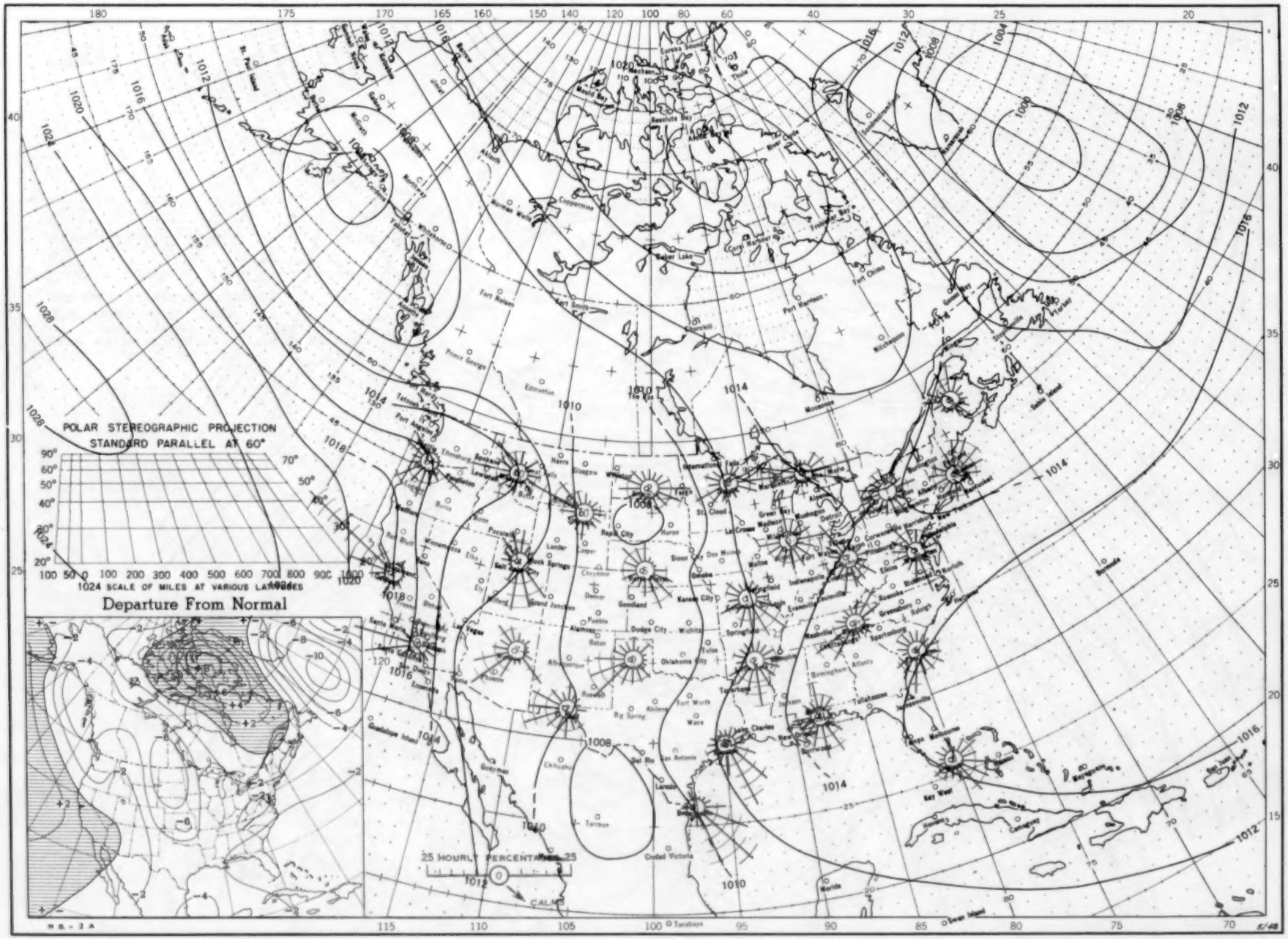
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, April 1955.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

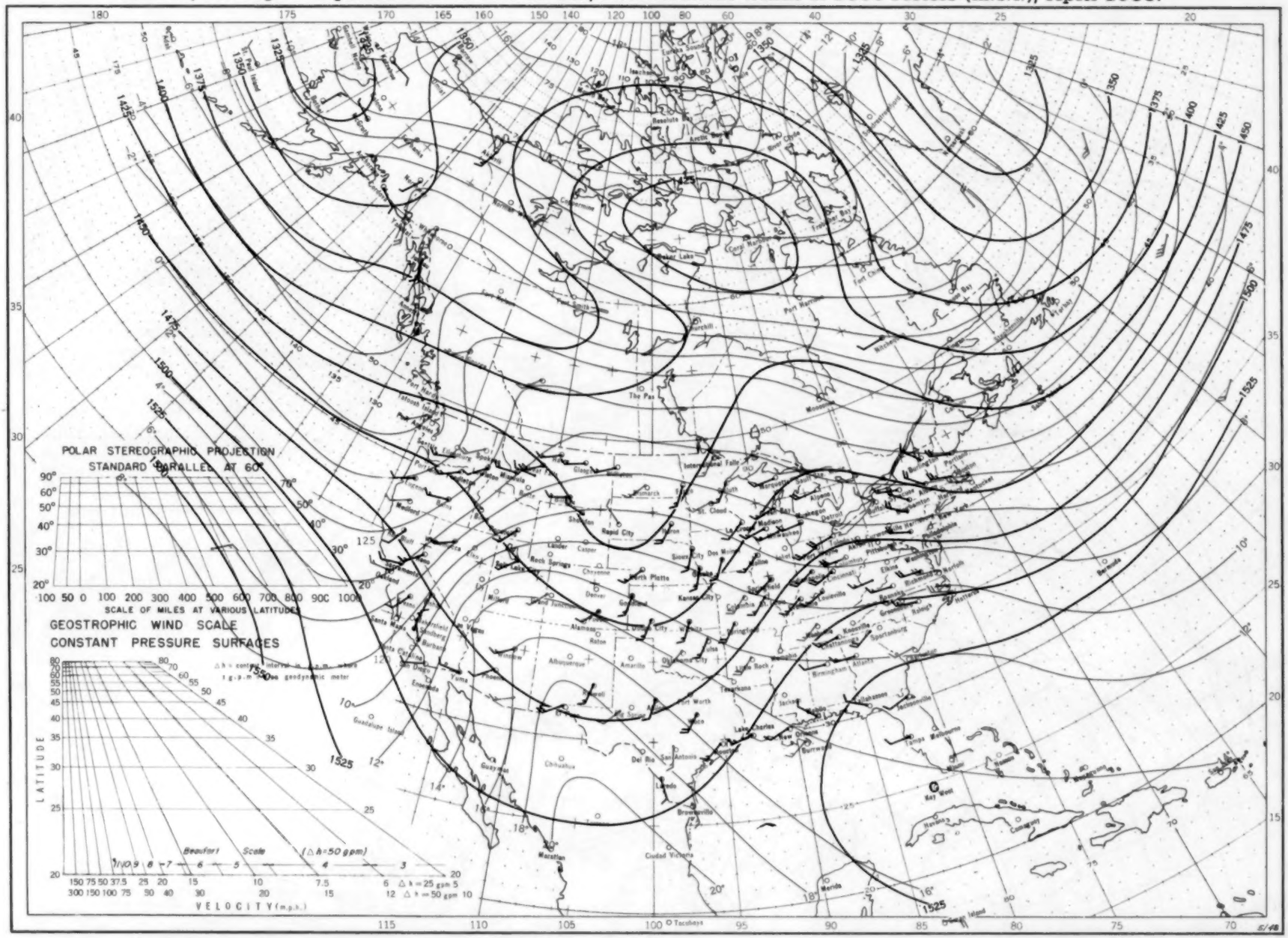
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, April 1955. Inset: Departure of Average Pressure (mb.) from Normal, April 1955.



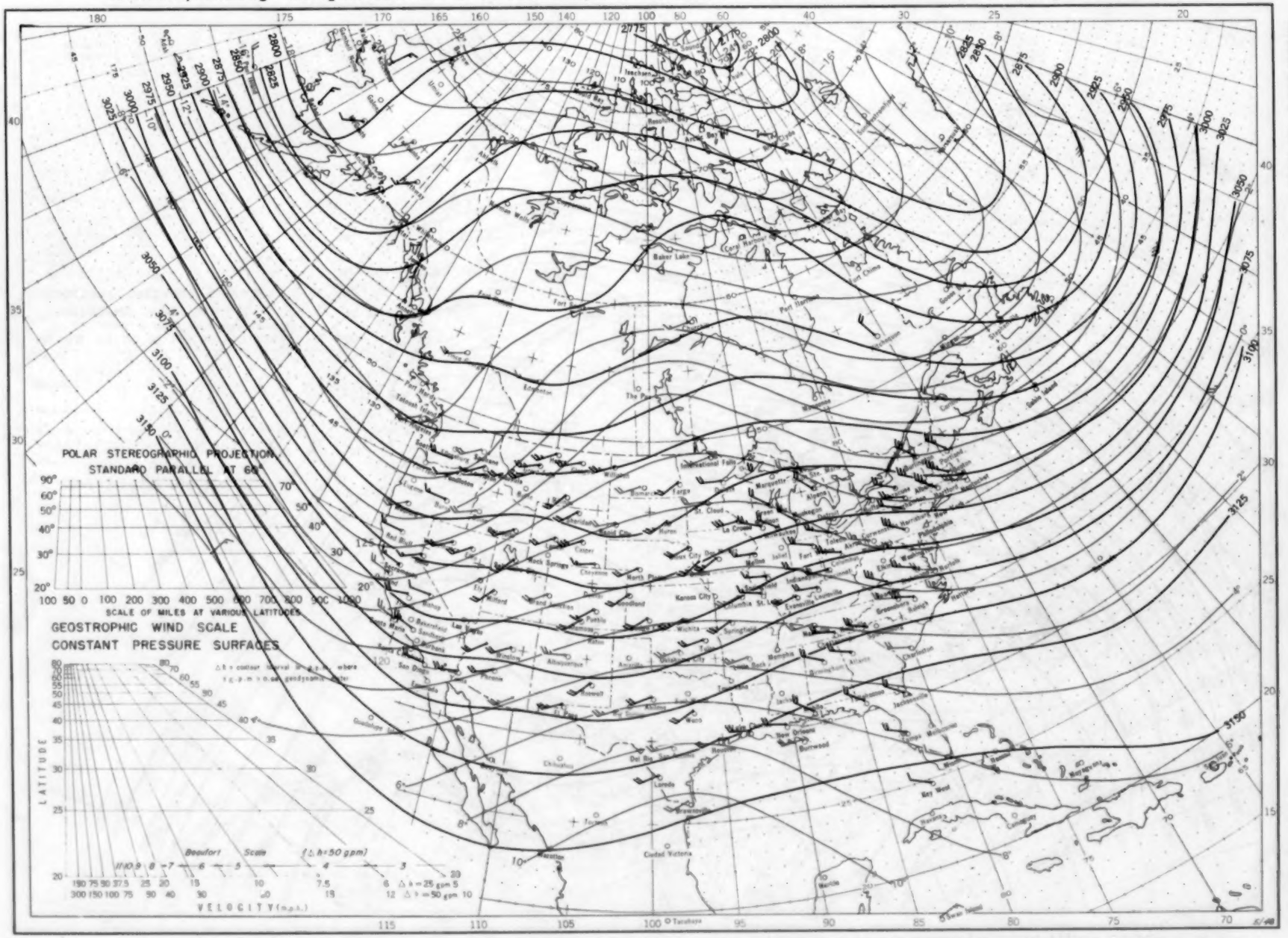
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), April 1955.



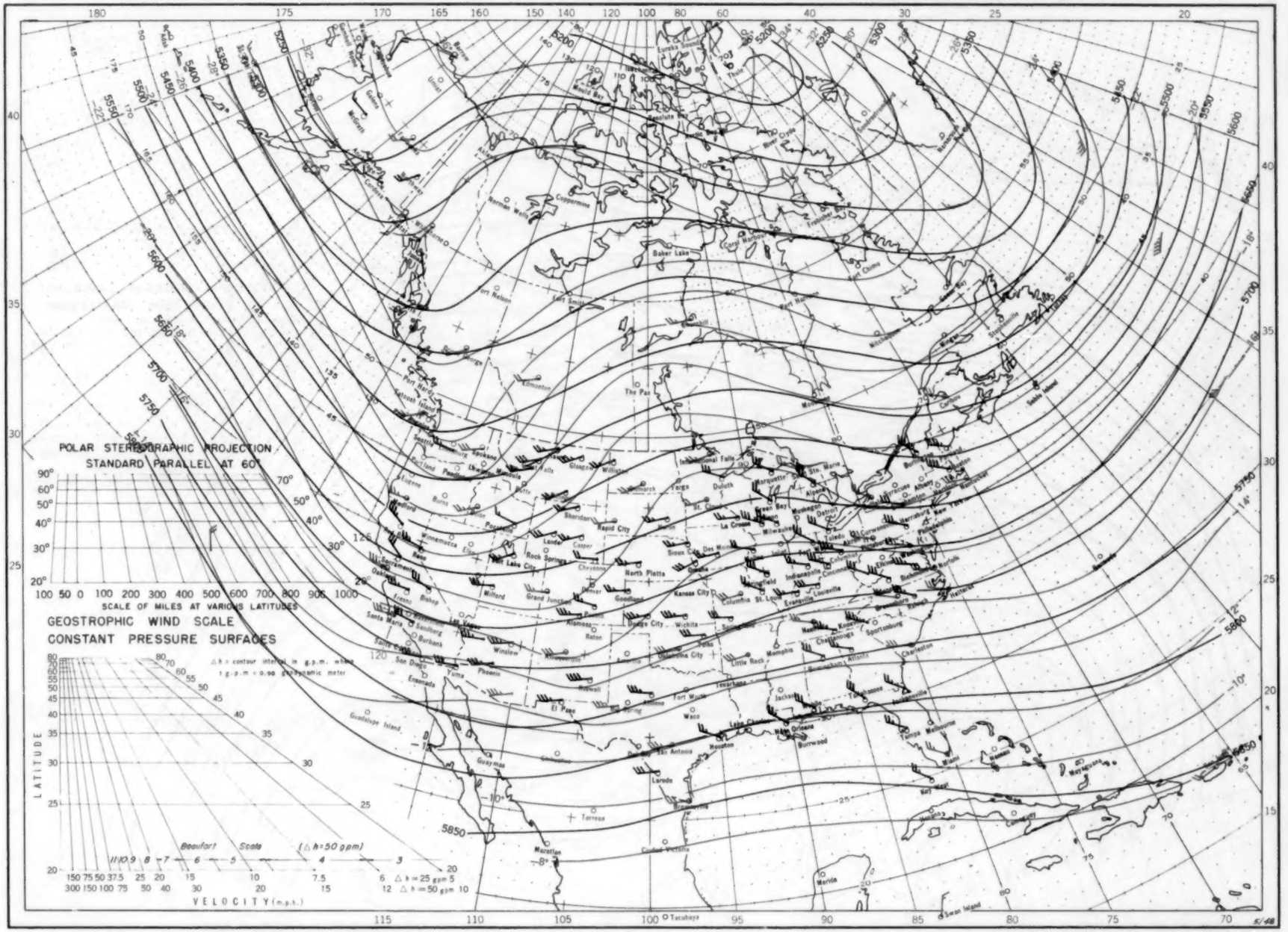
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), April 1955.



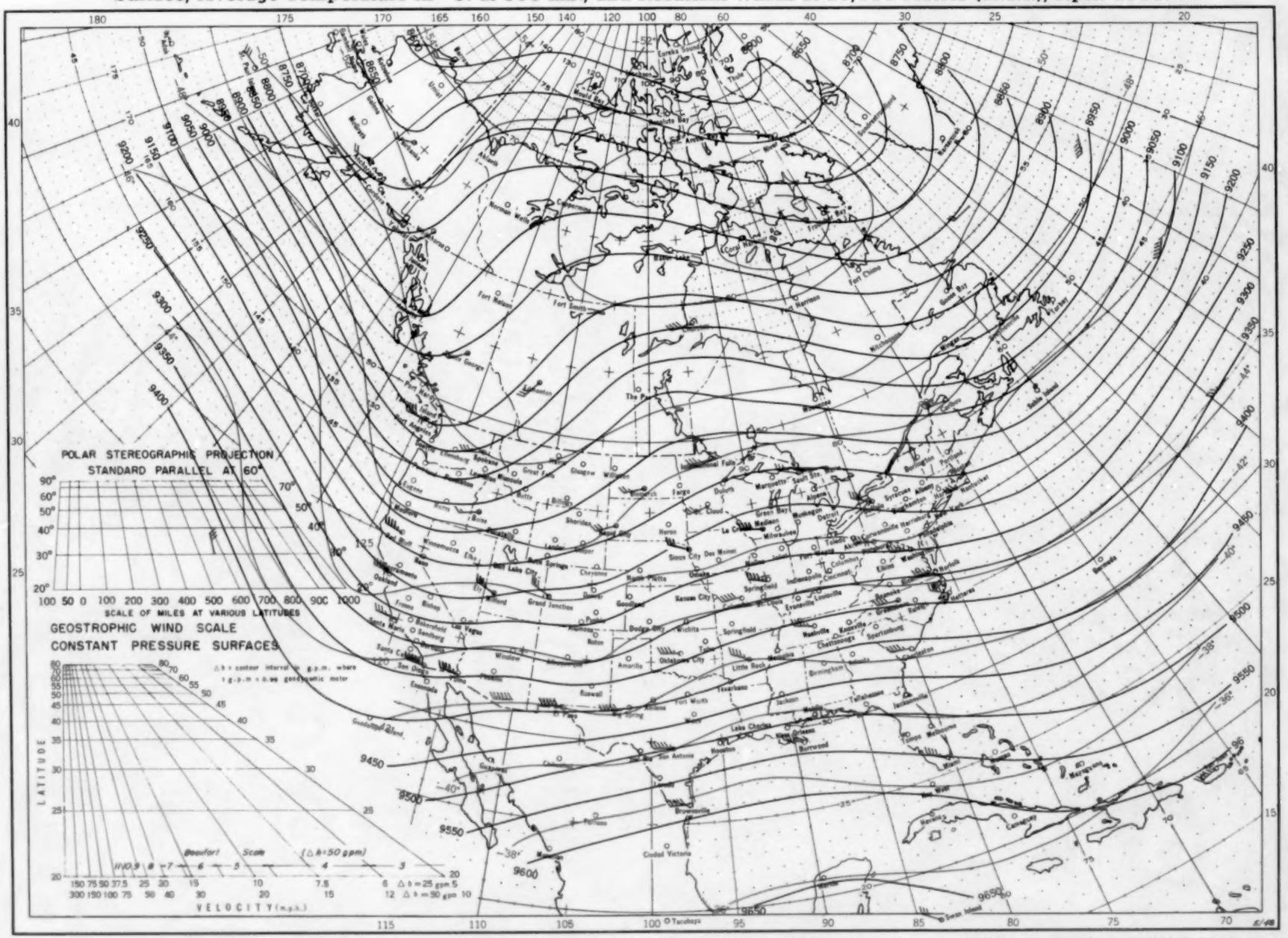
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), April 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), April 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.